Diss. ETH No. 27030

Robotic Landscapes

Topological Approaches to Terrain, Design, and Fabrication

Ilmar Hurkxkens

DISS. ETH NO. 27030

ROBOTIC LANDSCAPES: Topological Approaches to Terrain, Design, and Fabrication

A thesis submitted to attain the degree of
DOCTOR OF SCIENCES of ETH ZURICH
(Dr. sc. ETH Zurich)

presented by
ILMAR U. HURKXKENS
Master of Science, Delft University of Technology

born on 04.08.1982
citizen of The Netherlands

accepted on the recommendation of
Prof. Christophe Girot (Supervisor)
Prof. Marco Hutter (Co-Supervisor)
Prof. Matthias Kohler (Co-Supervisor)

2020

Abstract

The practice of earth-moving is an increasingly important undertaking in creating and sustaining resilient urban and landscape environments. The recent increase in natural hazards like sea-level rise, landslides, floods, and drought, point to the delicate balance that exists in our ecosystems. While heavy equipment used to construct large-scale earthworks in response to natural hazards has existed for over a century, they are incapable of reacting to the constant progression of landscape processes driven by environmental change. As such, taking informed and regenerative action on any of these challenges has proven problematic.

Situated in the context of landscape architecture, this dissertation presents a new design and construction approach to working with terrain. Building upon recent advances in surveying techniques and mobile robotic fabrication with heavy equipment, it investigates new design processes and robotic formation strategies in natural granular material. It introduces digital terrain modelling tools based on distance functions that support a dynamic modelling approach by integrating information, design, and fabrication techniques. This dissertation implements these tools in combination with lidar scanners and robotic platforms, to propose adaptive, emergent, and open-ended formation strategies for earth-moving practices. It outlines a reflexive design process that is elaborated between surveying, modelling, and simulation methods in order to support the design and fabrication of terrain structures that evolve over time. Here, form and forces are equally considered in the investigation of earthworks in response to erosion, transportation, and sedimentation processes in natural environments. The dissertation formulates four core concepts of dynamic formation—substance, process, grammar, and form—and identifies constraints for the application of robotic fabrication in the terrain.

This dissertation argues for earthworks capable of mediating performance between ecological and urban landscapes in opposition to creating predefined and static landscapes for an ever-changing environment. By designing topological rules to transform granular material into functional structures, it searches for a newfound equilibrium informed by natural and robotic processes in terrain.

Zusammenfassung

Die Gestaltung von Terrain ist ein zunehmend an Bedeutung gewinnendes Instrument zur Erstellung und zum Erhalt einer widerstandsfähigen urbanen und ländlichen Umwelt. Die aktuelle Zunahme von Naturgefahren wie der Anstieg des Meeresspiegels, Erdrutsche, Überschwemmungen und Dürren weisen auf das empfindliche Gleichgewicht hin, das in unseren Ökosystemen besteht. Seit mehr als einem Jahrhundert werden als Reaktion auf Naturgefahren schwere Baumaschinen und großflächige Erdarbeiten eingesetzt, die jedoch nicht in der Lage sind, auf die konstante, durch Umweltveränderungen getriebene Evolution von Landschaft zu reagieren. Daher haben sich bislang informierte und regenerative Maßnahmen zur Bewältigung dieser Herausforderung als problematisch erwiesen.

Diese im Kontext der Landschaftsarchitektur stehende Dissertation stellt einen neuen Entwurfs- und Konstruktionsansatz für die Arbeit mit Terrain vor. Aufbauend auf den neuesten Entwicklungen in der Vermessungstechnik und der mobilen robotischen Fabrikation mit schwerem Gerät werden neue Entwurfsprozesse und robotische Formbildungsstrategien mit natürlichem granularem Material untersucht. Es werden digitale Werkzeuge zur Geländemodellierung vorgestellt, die auf Abstandsfunktionen basieren und einen dynamischen Modellierungsansatz durch die Integration von Informations-, Entwurfs- und Fabrikationstechniken unterstützen. Diese Werkzeuge werden in dieser Dissertation mit Lidar-Scannern und Robotikplattformen kombiniert, um adaptive, in konstantem Wandel begriffene und ergebnisoffene Formationsstrategien für Erdbewegungspraktiken vorzuschlagen. Ausgearbeitet wird ein reflexiver Entwurfsprozess zwischen Vermessungs-, Modellierungs- und Simulationsmethoden, um den Entwurf und die Herstellung von sich stetig transformierenden Geländestrukturen zu unterstützen. Dabei werden sowohl die Form, als auch die massgeblichen Kräfte gleichermaßen bei der Untersuchung von topographischen Strukturen als Reaktion auf Erosions- und Sedimentationsprozesse sowie Geschiebetransport in natürlichen Umgebungen berücksichtigt. In der Dissertation werden vier Kernkonzepte der dynamischen Formbildung formuliert: Substanz, Prozess, Grammatik und Form initiieren ein Abhängigkeitsmodell für die Anwendung der robotergestützten Fertigung im Gelände.

Diese Dissertation plädiert für neue Erdbauwerke, die in einer sich ständig verändernden Umwelt und im Gegensatz zu vordefinierten und statischen Landschaften in der Lage sind, zwischen den Stärken ökologischer und urbaner Landschaften zu vermitteln. Durch neue topologische Regeln für die Umwandlung von natürlichem, granularem Material in funktionale Strukturen, sucht sie nach der Wiederherstellung eines neuen Gleichgewichts, das sowohl von natürlichen als auch robotischen Prozessen im Gelände beeinflusst wird.

Acknowledgement

I write this acknowledgement with gratitude to the people who gave me the opportunity and supported me in various ways throughout the development of this dissertation.

First of all, I want to thank my advisor, Prof. Christophe Girot, for guiding my research. I am extremely grateful to him for inspiring and challenging me, and allowing for time and freedom to develop my own ideas. Working amongst colleagues in his teaching and research group has profoundly influenced my attitude towards landscape design; his vision and insight are deeply rooted in the topology of this work. I also wish to thank Prof. Marco Hutter, whose robotic excavator provided the foundation for this research. His ground-breaking work allowed this dissertation to think and build on actual terrain. I am particularly thankful to Prof. Matthias Kohler for instituting my perspective on robotic applications and belief in design. This also counts for Prof. Fabio Gramazio, whose comments never fail to sharpen my understanding of digital technologies. I could not have navigated this journey without their observations and suggestions.

I am sincerely thankful to NCCR Digital Fabrication in general, and Dr. Russell Loveridge in particular, for supporting the research. It provided me with a stimulating research environment and has led to many fruitful collaborations within and beyond the department of Architecture at ETH Zurich. Heaps of thanks go to Dominic Jud from the Robotic Systems Lab, for the many things I have learned from him on autonomous excavation and the exiting days on the test field. I want to extend my thanks to his students Samuel Zimmermann and Fabian Grigis, who helped make the aerial lidar system a reality. This holds true for Gonzalo Casas from Gramazio Kohler Research, who was always ready to answer the many questions I had on integrating design and fabrication. Here I also want to thank Dr. Tom van Mele from the Block Research Group, as he helped to frame and facilitate this integration. Very special acknowledgement and gratitude go to Dr. Mathias Bernard, working with him was a real pleasure. His engagement in the development of digital terrain modelling tools was truly instrumental and inspired my conception of topology.

The experiments carried out within the design research studios would not have been possible without an incredible teaching team. I am thankful for all their support and advice, but also that I can call many of them my friends today. First of all, I want to thank my colleague Fujan Fahmi for helping to frame the experiments, form the studio work, and find ways forward over bumpy roads. These thanks extend to my colleague Benedikt Kowalewski as well, always providing solid ground for the studios to build upon. A lot of thanks go to Dr. Mirjan Ammar and Jesús Medina Ibáñez from Gramazio Kohler Research. To Ammar, for introducing me to the robotic mechanism, his commitment in developing robotic processes, and guidance on the course of this research in general; and to Jesús, for keeping the robotic compass of the studios and for his diligence with me and the students. Furthermore, I would like to thank the panel of international experts who devoted their time to review the design experiments: Ana Abram, Dr. Krishna Bharathi, Prof. Mario Carpo, Asst. Prof. Benjamin Dillenburger, Assoc. Prof. Dana Cupkova, Prof. Pia Fricker, Prof. Teresa Gali Izard, Asst. Prof. Jane Hutton, Maj Plemenitas, Prof. Jörg Stollmann, and Martina Voser. Additionally, my thanks go to the following experts that have contributed in various ways to this research: Prof. Paolo Burlando, Sasha Cisar, Dr. Kurt Heutschi, Dr. Andrew Kos, Fiona Maager, Dr. Brian McArdell, Prof. Peter Molnar, and Dr. Melanie Salvisberg. Not least of all, I am extremely thankful to all my students over the last years, for all their hard work, for their phenomenal achievements, and for believing in their designs.

The experiences and conversations I had over the last years with colleagues, collaborators, friends, and family are equally valuable as well. I thank all the organizing parties of the venues that enabled me to present the developments of this work, which allowed me to come across incredible research centers amongst others in Berkeley, Berlin, Cambridge MA, Delft, and Sydney. My gratitude goes to Dave Pigram and Nicholas de Monchaux for pointing me in the right direction. I want to thank James Melsom for the field trips and for providing a never-ending stream of new ideas, and Fabian Bircher, for exploring the limits of robotic systems with me. Furthermore, I am indebted to Filip Geerts for instilling my sense of the territory, and for giving the overview of the whole. For always being ready to edit my thoughts, I want to thank Salomon Frausto, who also helped to compose this document. I would like to express my gratefulness to my mother and father for encouraging me in the pursuit of constant change, and to my brother and sister, for always being there to provide welcome relief. Finally, for the countless daily walks, and for keeping me level in rough terrain, I would like to thank my dog Pixie.

Contents

Chapter 1

Introduction: A Granular Process

> *"Words and rocks contain a language that follows a syntax of splits and ruptures. Look at any word long enough and you will see it open up into a series of faults, into a terrain of particles each containing its own void. This discomforting language of fragmentation offers no easy gestalt solution; the certainties of didactic discourse are hurled into the erosion of the poetic principle."*
>
> —Robert Smithson [1]

1.1 Motivation and Background

In a meeting at the start of this project with my supervisors, a comment about technological innovation in design was made. When experimental research is combined with research by design, they can act as opposite forces towards the same goal: the development of new procedures and knowledge. While experimental research develops new tools and techniques, research by design develops new insights and understanding, which in turn can be the driver for the development of new tools and techniques. As such, research by design acts in the opposite direction of experimental research, consciously extracting rules throughout the research process towards qualification and rationalisation, see also Section 1.3. The recent technological development in on-site robotic excavation equipment can therefore benefit from research by design that is oriented towards terrain modelling in landscape architecture. The following introduction gives a background to design in terrain and discusses the research methods used in this dissertation.

The development of hydraulic equipment in the 19th century has changed the way local materials are resourced, and traditional construction techniques are applied in landscape architecture. The ease of material manipulation and transport has replaced the value of handcraft and careful manual assembly. Before the advent of this fluid power, minimising earth movements were more a necessity than a goal. It required a thorough knowledge of the lay of the land, its topography, water flows and soil build-up. Without economical constraints in earth-moving, a site can be transformed without regard to local materials or natural processes. As current landscape construction practices are largely driven by hydraulic equipment, they are often accompanied by extensive material removal and delivery to and from a site [2]. Combined with the global proliferation of grading equipment, it has led to a uniform approach in the shaping of terrain through standardised infrastructural earthworks projected over the landscape[1]. This practice has neglected the intrinsic value of site leading towards a loss of performance and meaning that exist in the specificity of every terrain.

The alteration of the ground has always been imperative in support of civilisation throughout history. Ranging from basic survival in the redistribution of floodwater at the Faiyum Oasis in Egypt 1800 BCE, to the creation of sacred mounds in the Neolithic period 2600 BCE at Avebury, Southwest England [4, p. 59], terrain modelling practices have always facilitated all aspects of public and private life. The recent convergence of urban growth and climate change increasingly superimposes natural systems with built-up areas [5]. While centuries

---

[1] In comparison to architectural discourse, the International Style was criticised by Kenneth Frampton towards the end of the 20th century to re-introduce local traditions and aspects of "ground" within the architectural project against the globalisation of architectural form [3]

of protective measures against natural hazards created a seemingly safe environment, current insights show that there exist an increase of natural hazards driven by human alterations of ecological systems [6]. Here, the interaction between gravity and matter follows the path of least resistance towards a dynamic equilibrium. In this ever-evolving landscape, large-scale construction practices of the last century have had a negative impact on sites because of the failed integration of ecological, sustainable, and landscape architectural considerations.

Two recent projects come to mind that have composed a new landscape bringing together aspects of form and performance in terrain. The first, by the landscape architects H+N+S, is situated next to Schiphol Airport and is made out of pleated earth ridges that reduce ground noise from aeroplanes taking off [7]. This expressive topography effectively cuts noise nuisance in half for the adjacent neighbourhoods and invites leisure activities. The second, by Georges Descombes and ADR, rehabilitate the Aire River near Geneva. The channelled bed of the river was widened by a new, clear-cut topology preventing seasonal flooding to leaves its banks (see Figure 2.7). It allows the fluctuating water to carve a new landscape over time, increasing the ecological value as well as creating a new kind of promenade [4, p. 326]. These two projects show that an intelligent combination of form and process can lead to meaningful and sustainable landscapes.

Recent movements in landscape urbanism [8] and landscape infrastructure [9, p. 13], make a plea towards a broadening of the discipline to include larger territorial systems. Both directions aim to intervene in the broader landscape systems like natural processes or physical phenomena focused on performance. With rising water around the globe and the pressure of increasing population density, the landscape seems to be reduced to a form of "biomimicry" [4, p. 338]. In recent practice, form tends to stay within the confines of the private garden or small park, whereas the larger landscape seems only to exist in support of infrastructure or ecology.

While the architectural discipline is founded in the tectonic expression of buildings, landscape architecture seems to have forgotten its disciplinary origin of shaping the form of the landscape, being mostly oriented towards park and garden design [10]. Both disciplines tend to neglect the physical shape of the earth’s surface as an expressive material that is modulated by natural and cultural forces over time. The topology project from the Chair of Landscape Architecture, ETH Zurich aims to recover landscape architecture as a discipline that integrates the physical, scientific, and poetic aspects of a particular site into a single meaningful whole [11, p. 8]. It looks for a new intelligence of terrain by encompassing all its continuity and complexity. In this sense, it is searching for methods and techniques to uncover the potential of a specific place.

This research seeks to extend the topology project to cover the geometry of the ground: the organisation of spatial relationships and proximities within surface structures. The craft of responding to—and shaping of—the earth's surface is seen as a vital aspect of a resilient design approach, proposing a new foundation for landscape architecture as a form-giving discipline for contemporary cities and landscapes. As part of the research project 'Construction Robotics' from the On-Site Digital Fabrication research stream of the NCCR Digital Fabrication at the ETH Zurich, this dissertation examines construction processes that shape found material such as soil or gravel. More specifically, it investigates natural granular material in the scales from clay to cobble (see also Section 4.2.3). The construction processes are based on the capabilities of the robotic platform HEAP, equipped with force controllable actuators as well as a novel approach to planning and control of a robotic system [12]. This robotic platform was developed over the same time-span of this research by Dominic Jud et al. from the Robotic Systems Lab of Marco Hutter. The design component is explored as a collaboration between the Chair of Landscape Architecture of Professor Christophe Girot and the Chair of Architecture and Digital Fabrication of Gramazio and Kohler. As such, it investigates new design, modelling and construction process robotic for earth-moving using autonomous walking excavators. The research presented here occupies itself with the emerging field of digital landscape fabrication and explores the potential of robotic earth-moving.

This dissertation tests a model where the specificity of the site is integrated into the process of design and fabrication. It investigates terrain as a form, as a process, and as a substance; examines models of information, design and fabrication; qualifies robotic processes in granular material; identifies potential for robotic construction in dynamic environments; and develops digital terrain modelling tools that support a dynamic design and construction methodology. By applying advanced robotic construction methods, new topological designs in landscape architecture demonstrate the dynamic potential of a site. It investigates the transformation of locally resourced material into functional structures at various scales and time frames. In the reconciliation between form and process, a dynamic construction approach is recognised as a performative and meaningful method for future landscape architectural design.

1.2 Research Goal

The advent of robotic construction technologies for on-site applications will change the way landscapes can be conceived and constructed. While the architectural discipline has demonstrated the value of digital fabrication for over two decades, the potential of on-site digital fabrication for landscape design that goes beyond automation of existing practices is mostly unexplored (See 2.3.3). As such, there is a need for design research, tools and processes for robotic landscape fabrication.

The complex behaviour of granular material in terrain results in a form that can not be pre-determined. This condition has slowed the introduction of robotic fabrication in earth-moving considerably, requiring complex control systems to interpret the state of the material after every manipulation. On top of this, mobile robotic platforms have to navigate uncertain terrain and rely on robust mapping and localisation techniques. This dissertation is based on the hydraulic excavator for an autonomous purpose (HEAP), a customized Menzi Muck M545 developed in parallel to this research by the Robotic Systems Lab of Professor Marco Hutter. This machine implements novel force-controllable hydraulic cylinders in the chassis and boom that allows it to adapt to any terrain, and is equipped with lidar sensors necessary for autonomous operation [12]. On-site robotic fabrication processes with HEAP introduces a feedback mechanism to the construction of landscapes (see also Section 4.2.2) and enables the capture of in-between states of matter through sensor technology [13, p. 17]. The complete mechanism is shown in Figure 1.1, which is defined by the survey, the design, and the fabrication. Applying this robotic mechanism to digital design and fabrication allows for dynamic approaches in terrain. This dissertation looks at dynamic design and fabrication techniques in order to research and apply the landscape architectural potential of this new approach.

Working with terrain in landscape architecture involves almost all aspects of a landscape project and has a significant influence on the natural environment as a whole. This dissertation situates itself not as an all-encompassing methodology, but looks at formal and performative aspects of natural processes in the mineral dimension of terrain. It lends insights from other fields that have studied these aspects in detail, namely geology, geomorphology and hydrology. Whenever ecological problems or benefits occur through specific application of design strategies, these have been mentioned. A limit to the mineral grain size has been defined to come to clearly defined applications for the robotic platform. This includes clay, silt, sand, gravel and cobbles but excludes boulders or solid rock. This establishes a coherent design methodology as well as digital modelling requirements, and aligns with existing accessories for heavy equipment like shovels and buckets. The importance of scale is acknowledged in the formation of small- to large-scale structures and processes in terrain, allowing for varying computa-

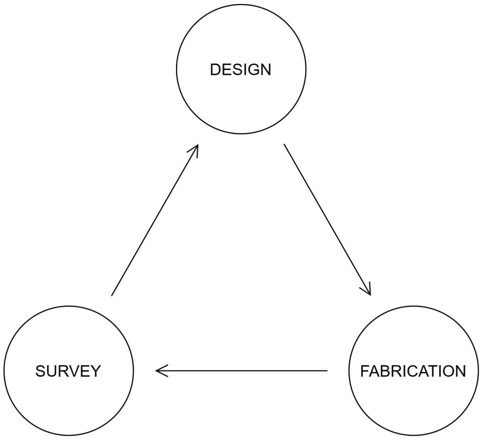


Figure 1.1: The three elements of the robotic mechanism. By linking them together, a dynamic design and construction approach is made possible.

tional approaches depending on the application.

On the advent of on-site robotic fabrication, this dissertation proposes a model where local materials and processes inform the rules and construction processes in the transformation of terrain. This provides a sustainable methodology in the use of granular materials in small- and large-scale landscape projects. It is mostly concerned with the development of design tools and design systems in earth-moving applications for small- and large-scale experiments of robotic formation. The aim of the research is to develop a dynamic design system based on topological rules that, in turn, can support future research in robotic construction methods for landscape architecture.

1.2.1 Problem Statement

As stated in the previous Section, robotic earth-moving as a design opportunity for landscape architecture is largely unexplored. The broader problem that is considered in this research can therefore be described as follows:

- What is the potential of on-site robotic earth-moving for landscape architecture?

Robotic earth-moving is a technically challenging task that needs to adapt to continuous changing site conditions. The shape of loose and granular material after it is manipulated is virtually impossible to predict. Instead of putting all the efforts towards the efficiency and precision of robotic earth-moving systems to reach a predefined geometry, one can accommodate this challenge by applying dynamic modelling techniques using the feedback mechanism that, in turn, also enables new dynamic design strategies. Therefore, this dissertation asks the following question:

- What robotic formation processes can be applied towards building resilient landscapes in dynamic equilibrium?

Design tools for robotic landscape construction are not readily available or tend to favour automation over expressive freedom. From digital fabrication in architecture we can learn that the integration of digital modelling and fabrication systems will open up new possibilities for design. With this in mind, the following technical challenge is considered:

- How can digital terrain modelling tools be extended to facilitate dynamic design and robotic landscape fabrication?

Based on these three questions, the following research objectives have been outlined in the next paragraphs.

1.2.2 Research Objectives

While the research group of Marco Hutter develops localisation, control, and mapping for HEAP, landscape architectural approaches demand larger elevation maps that include topography beyond the immediate surroundings of the robotic platform to design and understand the full project and complexity of landform structures. This can be achieved as part of the survey, providing formal and also mechanical properties of terrain using sensors for both the preparation and execution phase. Through filtering, segmentation, and analysis, it provides a terrain map as well as additional parameters that are essential for a dynamic approach. The design component of the robotic mechanism handles the modelling and simulation of natural granular material. As the terrain has to be scanned repeatedly to interpret the current state of execution or the project's evolution in time, it requires a digital modelling approach that is capable of dynamic updating. This is necessary to allow dynamic design constraints that are validated on performance before it is executed by the robotic platform. Therefore, this research implements aerial lidar technology (see also Section 3.2) to enable large-scale robotic terrain formation and develops an integrated parametric and computational terrain modelling tool essential to enable the robotic feedback loop. This contributes to a digital workflow from design to fabrication. As such, focus lies on advance surveying techniques and digital modelling tools:

- Implementation of surveying techniques using point cloud technology towards real-time feedback.

- Development of digital terrain modelling tools that enable dynamic design approaches.

Design processes are based on the capabilities of the autonomous walking excavator HEAP. Through the identification of the robotic mechanism, dynamic formation strategies that leverage the expressive capabilities of HEAP are developed. Procedural rules for robotic processes in granular material relies on material and fabrication constraints that are subsequently developed in ongoing experiments. These experiments lead to the development of direct information exchange between the design intent, modelling approaches and the robotic fabrication system. The following objectives are set to enable the study of dynamic formation in terrain:

- Implementation of a direct connection between survey, design and fabrication for experimental and large-scale fabrication.
- Development of formation strategies towards new practises and processes of robotic fabrication in granular material.

The modelling tools and formation strategies in granular material are explored in design scenarios to evaluate their landscape architectural potential. To design with evolving natural and robotic processes over time changes the design process. Instead of linear design development, it establishes an iterative process that loops between framing, forming and finding methods. The following objectives are set to study the potential of robotic earth-moving for landscape architecture:

- Implementation of a dynamic design system to enable the study of dynamic processes that change over time.
- Development of dynamic design strategies for large-scale landscape design in terrain.

1.3 Research Methodology

As mentioned in the introduction, design can drive technological innovation (see Section 1.1). Experimental research, well established in the technical sciences, involves some form of physical experiment or action that is quantified by the analysis of individual parameters. Here, new solutions can be put together out of newly arriving techniques and tools from other domains, or by combining existing practices and processes into new functionalities. [14]. Research by design, on the other hand, is carried out by the action of research *through* design. Here, new solutions are formed through substantial use of design by varying both object and context [15], which is validated by qualitative review. It functions somewhat in the opposite direction as experimental research, as it looks into the future for solutions of the present. As Dilnot [16] notes, the implication of newly acquired design understanding is that it can set the agenda for further research within the technological sciences, as such, experimental research and research by design act as two separate forces pushing technological innovation in landscape architectural design forward. This research implements research through design in small- and large-scale experiments to explore the potential of robotic technologies in landscape architecture. After every design or physical experiment, research methods and processes were evaluated in order to understand their potential. As design is an inherently reflective process, problem statements and objectives were reframed throughout the research. Both the design solutions and tool developments from this research were driven by this ongoing and granular process. Four core concepts of dynamic terrain—substance, process, grammar, and form—were distilled from this experimental design research and discussed in Chapter 4 and 5, respectively.

1.3.1 Team Work

The research is set up as an interdisciplinary study to foster the integration of design and technological research. As it includes professional expertise from both fields, interdisciplinary studies are certainly a necessity to explore robotic construction for landscape architecture. The need for robotic expertise is evident, which is combined with design modelling and design intelligence to come to physical experiments. For this purpose, the research was developed in close collaboration with the Robotic Systems Lab of Professor Marco Hutter to establish an immediate relationship between the robotic platform and design. The Chair of Architecture and Digital Fabrication of Professors Gramazio and Kohler supported the implementation of advanced digital fabrication techniques using their long-standing know-how in this field. In collaboration with Digital Building Technologies of Professor Benjamin Dillenburger, modelling tools using volumetric methods were applied to digital terrain models. Finally, this dissertation is carried out within the Chair of Landscape Architecture of Christophe Girot, which has researched modelling tools and landscape understanding from a point cloud base model for over a decade. This experience and support proved indispensable for the development of on-site surveying and design methodologies with found material. The interdisciplinary approach applied in this research was therefore fundamental to the development of modelling techniques, physical experiments, and design processes.

1.3.2 Tool Development

Using point cloud techniques—developed at the ETH Landscape Visualization and modelling Lab of the Chair of Landscape Architecture, Professor Christophe Girot [17, p. 34]—the research looks at new landscape structures using locally resourced materials. It investigates the shaping of loose and granular material for terrain grading purposes. As it is virtually impossible to model the heterogeneous size and shape of local materials, the terrain was conceived as a surface and operated upon using implicit modelling methods. This allows for abstraction in the design phase while leveraging dynamic construction processes implemented on the robotic platform. Independent of the task, whether it be designing or fabricating, the research developed a set of specific modelling tools based on a point clouds obtained by terrestrial, aerial, or mobile laser scanners.

To implement a dynamic design and construction approach, digital geometry has to be modelled using parametric or algorithmic methods to enable direct communication between information, design and fabrication systems. Due to the nature of existing 3D modelling programs that have been developed for industrial design or architecture, it has proved problematic to use off the shelf solutions due to the inherent complexity within landscape structures. This research develops digital terrain modelling tools that overcome existing terrain modelling limitations (see also Section 2.3.2) and enables the exchange of information with the robotic platform HEAP that also uses a multi-layer 2.5D mapping package for ROS called Grid Map. Through the development of implicit modelling methods using Python, the research implements modelling tools within the visual programming interface Grasshopper 3D of Rhinoceros, extending its use to designers without prior programming knowledge. These implicit modelling methods operate directly on elevation rasters, which makes the exchange of elevation data for use in simulation packages of hydrological or mass movement processes affordable.

Designing and fabricating with robotic processes in granular material relies on a connection to the robotic platform, whether this is implemented on a small scale robotic arm or on HEAP. The connection to the robotic operating system ROS was established using COMPAS FAB[2] developed by Gramazio Kohler Research. It allowed this research to focus on specific terrain implementations relating to point cloud surveys and design tools without the need to start from scratch. While the digital modelling tools are still to be translated to a COMPAS implementation, this approach will allow for direct interoperability with the other research contributions and to establish a solid computational base for future research in this field.

1.3.3 Experiments in Dynamic Formation

To overcome the gap between on the one hand physically modelling loose material like sand, and on the other the 3D modelling of terrain structures, this research carried out both small-scale physical experiments as well as experiments in large-scale landscape design in three design research studios (See Chapters 4 and 5). The small scale experiments were tested in a sandbox aimed at materially informed formation strategies using digital processes. Digital-physical design tools form the ideal design systems for robotic fabrication as the processes are similar to real-world applications. The material constituents that are modelled form a crucial component in the design constraints and were tested in small-scale setups to determine their performance using methods from the fields earth science [18]. Developed for the design research studios in collaboration with Gramazio Kohler Research, a robotic arm enabled the interaction with granular material to explore dynamic landscape strategies. The complete setup consisted in various combinations of a robotic arm, a 3D scanner, a force sensor, an end effector and the sandbox. Controlled via computational design tools using Grasshopper and the programming language Python, the material was modelled by giving the end effector coordinates and/or forces to manipulate the sand. Through iterative scanning cycles, a loop was created, enabling a continuous formation process based on various landform parameters extracted from the sandbox. In this way, the design can be linked to a physical output by leveraging material computation without the need for complex simulations of soil dynamics. These experiments are not aimed at resembling the full-scale processes using HEAP but were conceived to explore robotic processes in granular material throughout all conceptual scales.

The experiments in the design research studios test new applications following principles of robotic construction in landscape architecture. The design knowledge gained in these experiments are aimed at the development of new design methodologies and processes. This knowledge is subsequently applied in a 1:1 demonstration made in collaboration with the RSL of Professor Marco Hutter using the autonomous walking excavator HEAP (see Section 4.4). This robotic

---

[2] COMPAS FAB is an extension to COMPAS, an open-source, Python-based computational framework for collaboration and research in architecture, engineering and digital fabrication initiated by the Block Research Group of ETH Zurich.

prototype is intended to explore the design space of robotic terrain modelling by studying the possibilities of terrain-slope, volume balance, and formal complexity, as well as linking the design environment to the robotic execution system. Through the integration of surveying, design and fabrication, a dynamic fabrication approach is investigated.

1.3.4 Experiments in Dynamic Design

The internal reflective process of design between framing, forming, and finding (see also Section 5.2.1), shifts towards reflexive processes using dynamic technologies. Similar to a reflective design process—where a design move is evaluated and re-framed by the designer—a reflexive design process is concerned with the rules that determine the next move. As such, the designer has to anticipate and react to topographic changes brought about through either natural or robotic processes. Through robotic technologies, it becomes possible to encode a robotic response that varies depending on the current state of the terrain in every iteration. As such, this process does not belong solely to the designer, but becomes a combination of topological rules, robotic processes, natural processes, and the material system. This reflexivity, the circular relationship between cause and effect, steers and directs the evolution of forms in terrain. It is investigated in the design studios through a recursive application of the robotic mechanism. In studying the chain of events by iteratively over surveying, modelling, and simulation, it becomes possible to establish a new dynamic equilibrium based on topological rules. By researching the potential of newly arriving technologies, insights from the design studios may provide new answers to a more sustainable and resilient material culture in landscape architecture.

The small scale physical experiments form an integral part of the design research at a larger scale. These experiments inform the dynamic design strategies for robotic construction processes and are applied throughout the design research studios running over a 3-year academic period. The studios look at various sites with natural processes where each study focuses on a specific landscape application. Robotic construction methods are explored by transforming local materials like sand or gravel in a dynamic topological definition towards performative topographic surfaces capable of adapting to natural processes over time. The method includes an adaptation to local landforms using point cloud surveying techniques and digital terrain modelling tools. Computational tools are implemented under the guidance of experts in their respective fields that simulate natural processes in terrain. This allows for an integrated design approach starting from the field survey up to the final conception of a landscape. Throughout the design experiments, tools and processes were iteratively tested and improved to allow for the continuous development of dynamic design methods in the design studios and in the physical experiments.

1.4 Thesis Structure

This dissertation is build-up around six Chapters, where Chapter 1 and 6 form the introduction and conclusion, Chapter 2 contextualizes the research while Chapters 3, 4, and 5 form the body of the work. These six Chapters are followed by an Appendix that documents the modelling plugin for Rhino 3D developed during this research.

Chapter 1: Introduction: A Granular Process forms the introduction to the subject matter, discussing the project background, research goal and methodology and gives an overview of the key terminology. The research objectives follow out of the problem statements. They are defined and grouped in three themes consisting of digital modelling, robotic formation, and dynamic design in terrain that are respectively developed in the body of this research in Chapter 3, 4, 5.

Chapter 2: Earthworks in Context starts with an overview of topological aspects of terrain along the concepts of substance, natural processes and form. This is followed by a discussion on the current state of the art and its limitation in digital surveying, design and fabrication techniques specifically directed towards loose and granular material.

Chapter 3: Encoding Terrain starts with describing the implementation of advanced surveying techniques and their resulting data structure. It is followed by outlining implicit modelling methods in preparation of the presentation of new modelling techniques based on distance functions and a new digital terrain modelling tool.

Chapter 4: Substance and Grammar: Dynamic Formation in Terrain starts with outlining aspects of material properties and robotic fabrication in terrain. It is following by the presentation of the small scale experiments that were executed as part of the design research based on specific robotic operation cycles resulting in the identification of dynamic formation strategies for natural granular material. It also gives an account of shaping terrain using HEAP on the ETH test site, demonstrating the integration of survey, design and robotic fabrication processes.

Chapter 5: Form and Forces: Dynamic Design in Terrain begins with an outline of design processes, topological modelling, and natural processes that conclude the identification of design and construction constraints in terrain: material constraints, progressive constraints, fabrication constraints, and topological constraints. This is followed by an elaboration of dynamic design techniques that are subsequently applied in the dynamic design experiments.

Chapter 6: Conclusion: Terrain Moves summarizes the body of the research, discusses current limitations, and concludes on the implication of dynamic design and construction process in terrain for future landscape architectural design. It lists the contributions of this dissertation and provides an outlook for future work in this field.

Appendix A: Documentation Docofossor provides an overview of all the tools available in the Docofossor plugin for Grasshopper, Rhino 3D, that were developed as part of this research.

1.5 Key Terminology

This dissertation focusses on dynamic processes in terrain in applications of robotic landscape fabrication using topological methods. Below is a small overview of the key terminology used in this dissertation using the Oxford English Dictionary as a source.

Dynamic relates to a process or system in constant change or motion of—or pertaining to—force. In this research, this concept has been connected to various systems relating to either design, natural processes, or robotic processes. In design methods, it relates to digital techniques, and for design strategies, in systems that achieve a change in the formal configuration of the terrain. In natural processes, it relates to the forces that produce a transformation within the material system. Moreover, in robotic processes, it relates to the inherent nature of the robotic mechanism and cybernetic thought.

Fabrication designates the action or process of constructing or manufacturing finished products. Digital-fabrication has become an established compound noun in the application of robotic technologies in architecture. The meaning of the word extends beyond pre-fabrication by applying these processes outside the factory using on-site mobile robotic platforms. Within the scope of landscape architecture and technology, it is understood more synonymous to the word construction, as it exclusively applies to on-site processes. Throughout this dissertation, the word fabrication is used when a relation to digital technologies is essential, whereas the word construction comes up in the alignment to—or in opposition of—conventional techniques.

Robotic designates the technology or science of the design, construction, operation, and use of robots and similar automatic devices. In this dissertation, both its technology in landscape fabrication and its instrumentation as a dynamic process is investigated.

Terrain is a tract of land, an extent of ground or territory. There are many words that indicate a particular meaning pertaining to terrain like the ground, soil, earth, topography, e.g., each of which focusses on a specific characterisation of the landscape. In this dissertation, the word terrain is specifically chosen as it designates physical features and configuration, oriented explicitly towards a qualitative valuation of landforms.

Topology needs special attention here. It designates the scientific study of "place" that is applied throughout the sciences of philosophy, mathematics, medicine, linguistics, social sciences, art and design [11, p. 34]. However, its most common use today relates to its use in the branch of mathematics concerned with surface properties in abstract space: elastic deformation of geometric figures independent of size and shape and unchanged by any deformation that is continuous, neither creating new points nor fusing existing ones. Girot et al. [11] link this meaning back to its origin by defining topology as a theoretical position and study of a particular place in the ordering of space, and by focussing on surfaces and networks and on their performance and meaning for landscape architecture as natural and cultural structures. This dissertation extends this topological design methodology to include computational methods specifically oriented towards structure in terrain.

Chapter 2

Earthworks in Context

> *"The environment must be organized so that its own regeneration and reconstruction does not constantly disrupt its performance."*
>
> —Christopher Alexander [19, p. 3]

2.1 Overview

This Chapter covers the context and theoretical background of this dissertation. It discusses the importance of working with terrain through the lens of landscape architecture and highlights existing and newly arriving instruments associated with earth-moving practices. As natural hazards are becoming an increasingly urgent problematic driven by climatic change, it traces historical positions and current insights aiming at recovering landscape resilience and cultural valuation of our terrains, and gives an account of current material practices in relation to the depletion of our environments, particularly on soils. The first part of this Chapter is structured by the recognition that terrain exists as a form, as a process, and as a substance. This is followed by an outline of the state of the art in the making of earthworks relating to surveying techniques, digital modelling tools, and robotic construction processes. This second part of the Chapter is structured by the realization that all instruments that partake in conceiving terrain (in the largest sense of the word) relate either to models of information, models of design or models of fabrication. Because robotic landscape fabrication is still in its infancy, it leans heavily on concepts borrowed from the field of digital fabrication in architecture and small scale experiments carried out in sandboxes over the last 20 years. This Chapter forms the starting point for the experiments and design frame of robotic formation and large-scale design using autonomous equipment in dynamic, natural environments.

2.2 The Topology of Terrain

The most common use of the word topology stems from the field of mathematics, where it describes the continuity and relationships in surface structures. Its many other meanings illustrate the ambiguity of the word throughout the fields of philosophy, biology, mathematics, linguistics, and design. The word topology originates from the Greek words τόπος (place, space) and λόγος (study, word, sense). In its original meaning, topology denotes a topographic study that includes the historical dimension of a particular place. A topological design approach as defined by Girot et al. [11] extends this original meaning in a theoretical position and practical method to landscape architecture (see also section 5.2.2). As Girot et al. [11] write:

> *"Topology creates a particular intelligence of terrain by encompassing all of its continuity and complexity: the gnosis of landscape embedded in the intrinsic value of a common place."—Girot et al. [11, p. 7]*

As such, this position extends relational topology to the landscape, where spatial proximities in surface structures impact ecological values and how the space exists for people. It highlights terrain and its structure as a key methodology for organizing space. The importance of terrain as a load-bearing material for civilization has always been true but tends to be forgotten. Working with terrain aligns with our primordial origins in the modification of the environment to serve our needs. As Vittorio Gregotti describes:

> *"The origin of architecture is not the primitive hut...[but] a stone on the ground to recognize a site in the midst of an unknown universe..."—Gregotti, 1983, Address to the New York Architectural League. In Frampton [20].*

Lewis Mumford also clarified that the shaping of the city relied on the shaping of earth, and therefore preceded it [21]. Where and how settlement took place in early cultures was dependent on the natural form of terrain. Sites were chosen by a mythical understanding of place, were landscape features like mounts or waterways signalled sacred meaning [4]. The evolution from nomadic to sedentary cultures also marks the shift in the way nature was perceived and controlled. Initially prescribed to god-like figures of earth, water, and wind, to a condition where humankind takes control of the landscape. The expertise and scale of irrigation defined to a large extent the rise of early civilizations in Mesopotamia and Egypt. Its demise, however, can likewise be attributed to failures in the same system. The importance of geomorphology today—where and how settlements are situated in relation to terrain—becomes clear in times of climate change. Landslides, floods and droughts increasingly endanger cities around the world. The disconnect between the natural intelligence in terrain and modern civilization has led to a disruption in ecological systems. It makes clear that still today, earth, soil, and rock are the load-bearing material for any society to prosper [22].

In architecture, the difference between a functional building and how it is expressed as a meaningful structure for people is denoted by the term *tectonic*[1]. It refers back to its original meaning in principles or methods of making. It gives value to how materials and forces come together in a structural form that is associated with its making. A similar singular term for landscape architecture does not exist. However, Hutton [2] frames a revised definition for landscape architecture of the tectonic as described by Frampton [23]. Here, a tectonic reading of the landscape recognizes its particular material production processes and its evolution over time. She identifies five categories as driving factors in the formal expression of landscape: geology, constructed terrain, local and introduced materials, living materials and maintenance. As opposed to architecture, it makes clear that "site" and "time" are fundamental to how landscape architecture exist both physically and as a form of art.

Working with terrain can, therefore, be distinguished between how it performs and how it is presented in landscape design. We can now summarize and simplify "topology" and "landscape tectonics" as belonging to three core concepts of terrain: Terrain as it exists as a form (topology), as a process (change over time), and as a substance (materiality). We will look at each concept in more detail in the following section.

2.2.1 Terrain as Form

Underlying Form

Topography is generally defined as the vertical and horizontal dimensions of a land surface. The importance of this underlying form in the creation of cities and infrastructure is illustrated by Kwinter [24] a borrowed concept in biology called *epigenetic landscapes*. The underlying form is understood as a landscape that conditions the forms set upon it (see Figure 2.1). Here, form acts as an ordering action, a deployed logic in terrain where any force follows the laws of least resistance. This logic is very apparent in how mountains erode over time and rivers flow downstream. However, without having insights into the slow transformation of terrain over time, natural hazards can have devastating impacts. As Violett-le-Duc reminds us in his treatise on the Mont Blanc:

> *Do not, however, complain if your lowlands are devastated, and your habitations swept away; and do not vainly impute these disasters to a vengeance*

---

[1] The word tectonic is also used in geology, describing large-scale structures and processes in the earth's crust.

> *or a warning on the part of Providence. For those disasters are mainly owing to your ignorance, your prejudices, and your cupidity. —Viollet-le-Duc [25, p. 377].*

This quote makes clear that an understanding of the underlying form in terrain is essential for resilient landscapes. It affirms the value of the form and evolution of terrain for rural and urban development. Furthermore, this concept inverts the typical approach of architecture first and then accounting for landscape.

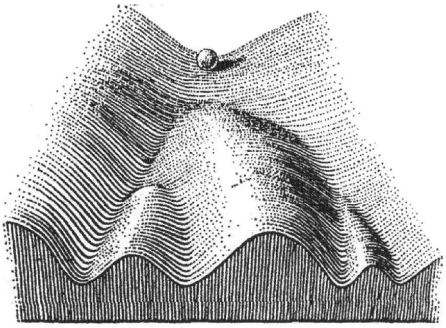


Figure 2.1: Illustration of an epigenetic landscape, where the underlying form determines the path of the objects set on it. From Kwinter [24], originally published in Waddington [26].

Describing Landform

While the evolution of landforms is well understood as a form and process, making a clear classification of its topography can be difficult. In daily life, we use qualitative and subjective distinctions like steep, rough or flat. A more scientific identification method applied by Landphair and Motloch [27] uses contour signatures to name landforms. Here, concave, convex, linear, and point-based signatures can distinguish mounts, swales, crests and plains. The same technique can also be applied using a drainage pattern. While these techniques are simple, they do not translate easily to a meaningful digital representation. Geomorphometry is the discipline that occupies itself with the quantitative analysis of land surface using mathematical and statistical image processing techniques. Methods range from encyclopaedic, by subdivision, or by hierarchy (see Westort [28] for more discussion). Here, discrete geometric primitives can be approximated in terrain while continuity can be assessed by looking at parameters like gradient, aspect, and curvature 2.2. To overcome the problem of scale, we can differentiate landforms between facets and elements: facets share gradient, aspect, and curvature while elements share plan and profile curvature. Many more descriptions exist for more applied and practical considerations like watersheds or mountain ridges [29].

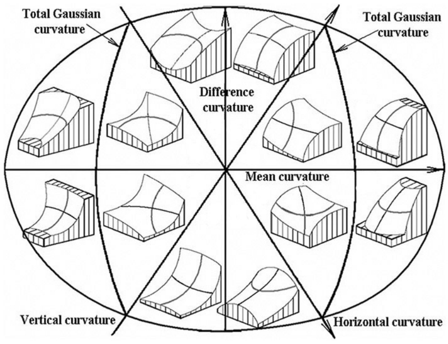


Figure 2.2: Landform classification based on curvature as defined by Shary, Sharaya, and Mitsusov [30, p. 95].

Formal Expression

In his book *Civilizing Terrains*, Morrish [31] uncovers the meaning of site through a vocabulary and accompanying landform for contemporary design. It provides landform analogies spanning from the spatial organization that make up a sacred place to a formal design language for urban terrain (see Figure 2.3). Represented in text and drawings, one can clearly distil the symbolic dimension that exists in the spatial relationships between landform and built form. These qualitative distinctions of landform are of interest for the discipline of landscape architecture [32]. They contribute to the evaluation of the formal expression in the terrain of any landscape architectural project. Strom, Nathan, and Woland [33] distinguished four categories in the visual presentation of earthworks. Geomorphic (1) expression reflects the geological forces and natural patterns of a particular site and blends into it. The architectural expression (2) consists of uniform earthworks defined by discrete geometric shapes. There exist a range of forms that fall between sharp and planar architectonic forms and naturalistic expression, which he defines as sculptural (3). Finally, the naturalistic expression (4) is a stylized approach that imitates a natural landscape. This approach goes back to the picturesque landscapes in England from the mid-eighteenth century and is still popular today. This categorization of landforms in naturalistic, discrete, and geomorphic form gives us an idea of how they are imagined and conceived. However, the current confusion in landscape design between how it performs and how it is presented is problematic. Recent responses to the increase in population density and climate change has reduced the geomorphic approach to a form of ’biomimicry’ [4, p. 338] where the landscape looks as if it arose from natural processes but does not perform as such. To give an example, the insistence of curved and smooth shapes over an architectonic expression in ecological design not only ignores the potential to leverage natural forces but neglects a symbolic and cultural dimension of a site as well.

Made Landforms

An architectonic expression in terrain is usually inspired from primary Euclidean forms or derivates thereof. Firstly, this can relate to its pure mathematical description and the ease of production in practice. Secondly, it refers to an ideal artificial form or perfection outside of its production means, often aspired in art and architecture to distinguish a pragmatic product to a product of the mind [34, p. 93]. While every landscape project involves some form of earth-moving, pragmatic projects like river engineering or roadwork make up the most significant modifications in terrain. Bélanger [35] therefore argues for an inclusion of infrastructure to the realm of the landscape architectural discipline. Infrastructural terrains can be categorised in a landform taxonomy to describe specific landforms like dikes, trenches, berms or terraces [36] and specialised excavation equipment exist for many of them [37]. The means of production for these specific landforms are developed and marketed to the point where techniques and processes have spread around the globe resulting in a uniform formal language, irrespective of its site. Their form can generally be expressed as a combination of geometric primitives; spheres, cubes, toroids, cylinders wedges and pyramids. The spline curve or a single curved surface is a particular case since it cannot be broken apart in a higher-order primitive, unless all parts fall onto an ellipse. However, it may be one of the most-used primitives in the design of earthworks like road embankments, paths, or river banks and has a long history as the line of beauty in landscape design known as the s-curve [38]. Thus these infrastructural modifications often use an architectonic expression and approach in the transformation of terrain even though this is not their first concern. Chapter 5 delves further into made landforms, and describes how the application of robotic construction techniques and processes can increase the design space in terrain and adapt intelligently to local site conditions.

Representing Terrain

The representation of terrain requires special attention. Through the application of force, a collection of particles will behave like a uniform solid [39]. This makes it notably different from architecture where the whole is an assemblage of discrete parts. The visual representation of terrain is therefore best represented as a continuous surface. In Figure 2.4 Imhof illustrates the difficulty in depicting a three-dimensional surface using common cartographic drawing techniques.

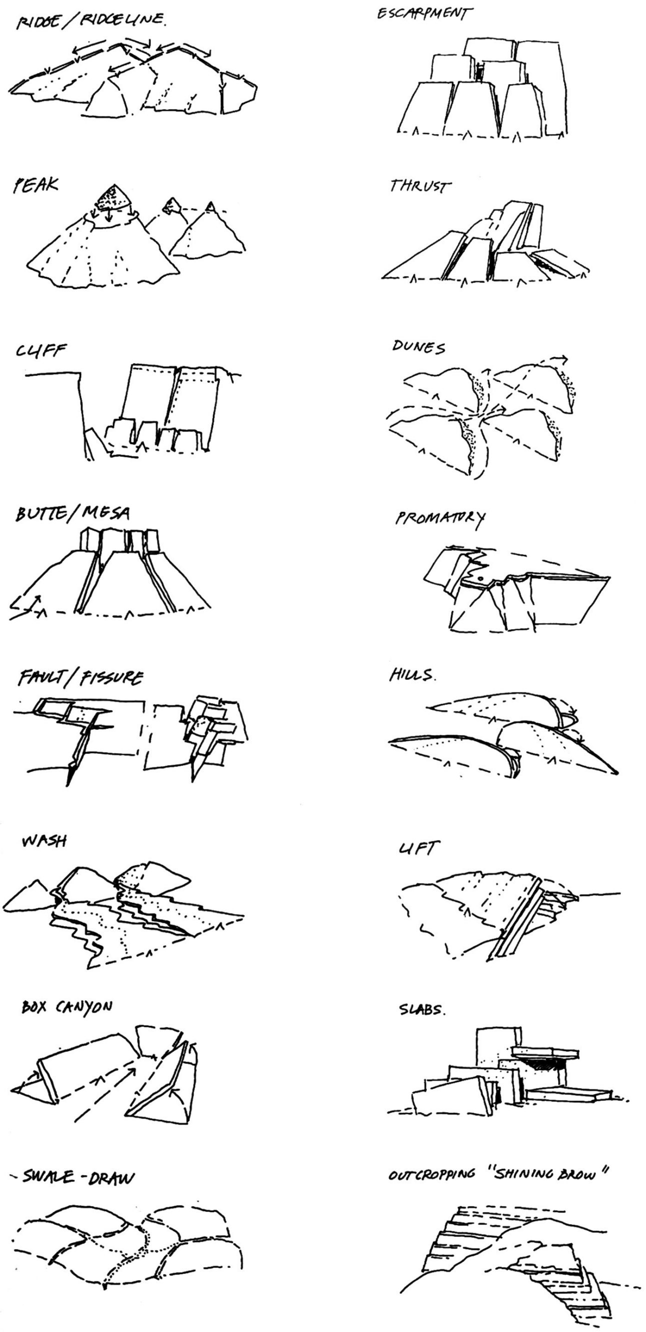


Figure 2.3: Design language of the urban terrain. The words and drawings stand for a basic spatial language for ordering and designing our earth in an attempt to bridge geomorphology and urbanism by Morrish [31, Drawing 41].

Here, it becomes clear that hachures, contour lines, or depth shading alone does not allow a correct understanding of the object. In all cases, it is necessary to add directional shading to see the form as it really is [40, p. 82]. Colour and diagrammatic drawing techniques can further inform the specific characteristic of the terrain. Still, it is hard to capture the many surface qualities due to the necessary abstraction in cartographic relief presentation. Towards this aim, 3D colour point cloud models achieve a much better view of the aesthetic reality of a site Girot [41]. It presents a complete view on the landscape in a cloud of particles. When we strip a point cloud model from all artefacts and vegetation and only look at the points that belongs to the terrain, similar problems occur as were described by Imhof. The addition of false directional shading or ambient occlusion is vital to comprehend its form. Digital point cloud models do offer the advantage that they can be animated easily. By changing the point of view, dimensionality is revealed through an interpolation from one frame to the next. Animation also allows to depict temporal aspects in terrain without having to resort to sequencing or diagrammatic superimposition in time. The implications for digital terrain modelling as a three-dimensional surface or as a cloud of particles is discussed in Chapter 3.

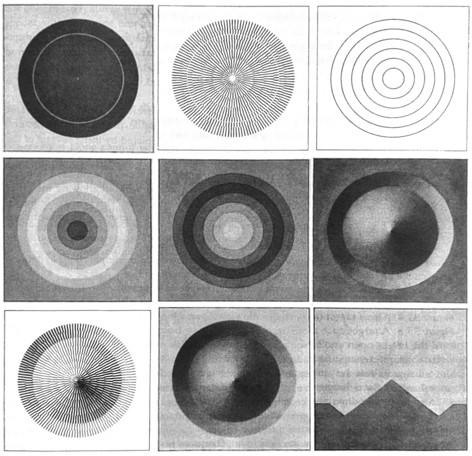


Figure 2.4: The problems and characteristics of depicting a circular cone using several forms of cartographic representation by Imhof [40, p. 82]. The bottom-right illustration depicts the cone in section for reference.

2.2.2 Terrain as Process

From the previous sections, we can conclude that form in terrain is nothing but a single frame of a system in motion. To understand how this form comes into being and evolves, we can look at the earth sciences. The following sections will give a brief overview and relate scientific findings to the field of landscape architectural design.

Natural Processes

Topographic or bathymetric features visible on or near the earth's surface are created by the interaction between internal tectonic processes and external processes on the surface that are of physical, chemical or biological nature [42]. They can be divided in hypogene action (volcanic, earthquakes) and epigene action (wind, water, life). In general, all natural processes can be traced back to (1) erosion, (2) denudation and (3) accumulation (see Figure 2.5) [32]. Natural landforms, while seemingly static, are in continuous movement. As such, forms are structurally stable moments within a continuously changing system in evolution [24]. Instead of progressing towards a final equilibrium with occasional local disruptions, it is now understood that their nature is inherently dynamic where small disturbances can lead to large effects [43]. Modelling their behaviour does not lead to a single determined outcome; instead, its properties are best described statistically; in the probability that events may occur. In planning, this has led to models predicting 10 or 100 year floods, based on past experience and prediction models. Inevitably, we see today that the equilibrium shifts itself, making many climate predictions of the last decades already outdated. It is well understood in textbooks on equilibrium analysis that there is no single outcome, and one should always apply measures of reason to any result. It is important that the designer fully understands the assumptions or consults with experts before applying simulation results in the design of terrain [44]. In short, making landscapes that are forever robust and resilient is virtually impossible in light of the nature of dynamic systems. Designing for change and future adaptation seems to be a more fitting approach [45].

Manufactured Processes

The alteration of the ground connected to the development of contemporary civilization now exceeds the natural processes in land surfaces around the globe [47]. While chemical fertilizers in the soil make up most of this data point, land levelling, trenching, and embankment building concurrent to earth-moving practices in relation to the metabolism of cities plays a part as well. The mixing of materials in landscape construction—where local materials are mixed with those sourced from great distances— results in a new material strata [48]. For example, these new strata are evident in the Sigirino Mound project undertaken by AlpTransit Gotthard AG and designed by Atelier Girot. Here, 3.5 million cubic metres of crushed rock from a tunnel excavation was placed on a hillside creating an artificial mountain topped with a mixture of rock and local soil forming a new

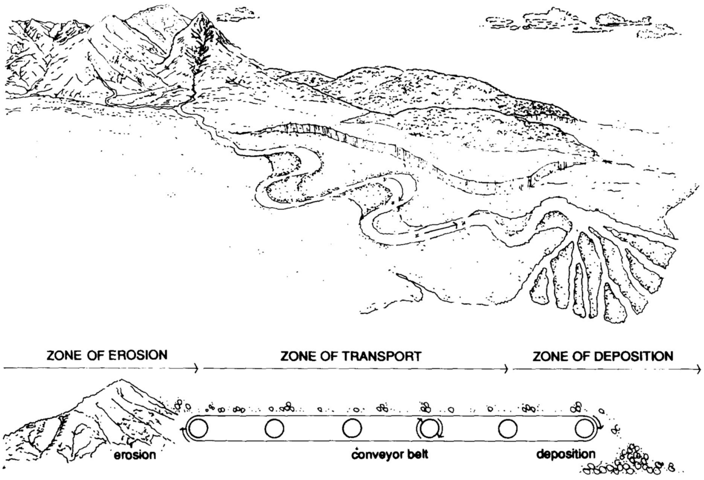


Figure 2.5: Conveyor belt analogy illustrating the zones of sediment erosion, transport and deposition by Kondolf [46].

ecological reserve [49]. The significant alteration of earth's ecosystems due to human activities has led to the definition of a new geological era: the Anthropocene [50]. In this process, landscape architecture, architecture and infrastructure have become more and more entangled into a single large artefact where the increasing complexity of our environment is slowly but surely becoming a continuous whole. The mechanical movement of material has invoked a debate between natural and artificial substrates and its ecological effects. A redirected focus on the actual process and performance subjected in terrain—whether natural or human-made — could lend a more operative approach to transform these dynamic environments [51]. However, there is a need for a better understanding of these processes and how they can be made available for design.

Far from Equilibrium

The term "maakbaarheid" origins from Dutch and indicates an analysis of the possibility of constructing something. It is often used in The Netherlands relating to the landscape: the extent to which we can make it as we want. The belief in the "maakbare" landscape found its peak in the post World War 2 era [53]. Large-scale infrastructural project like dams and dikes ignore the inherent dynamic nature in natural systems by rendering them static. This approach has led to a decrease in ecological value and an increase in natural hazards due to their failures around the globe. Recent reactions to this problematic include landscape urbanism as defined by Waldheim [8], landscape infrastructure [9] or ecological urbanism [54]. Here, a modification and transformation of fields and flows in ecological systems

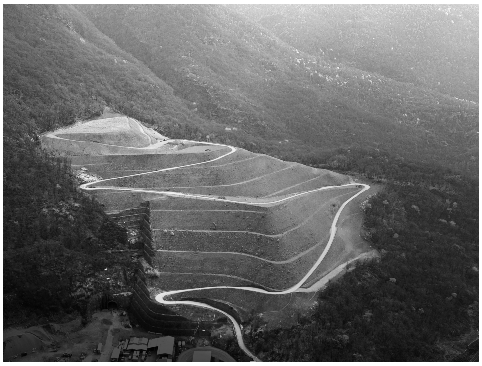


Figure 2.6: The material from the *Ceneri Base Tunnel* [52] forms the new geological strata of the Sigirino Mount by Atelier Girot. This manufactured landform ensures ecological continuity by aligning itself to the topology of the existing terrain, which was made possible by point cloud surveying and modelling techniques

are preferred over the arrangement of fixed objects. It has become clear that one cannot control the environment completely, and a symbiotic approach towards landscape processes is necessary for resilient development. The rehabilitation of the Aire River near Geneva is such an example. Here, a clear cut topography changes over time by the force of water forming a new natural floodplain (see Figure 2.7) [55]. However, this designed system is not in equilibrium, and as a result, a continuous transformation occurs, one by the force of water and one that is mechanical, maintaining the system due to unexpected erosion and deposition rates (which is necessary because the upstream and downstream stretches of the river remain channelled). A belief in the "maakbare" landscape has found a resurgence in recent technological and materials innovations. Instead of large-scale infrastructural projects, decentralized, small to medium scale projects using local materials and computation points towards a new understanding of our environment, and how we operate within it (see also Section 2.3.3).

Emergence

The idea of terrain as a stable and permanent entity is shifting today to an idea of constant change. Landscapes are influenced by dynamic fields and forces, making its evolution unpredictable. These systems are open, formless and operate in a non-linear fashion as a process [57]. As Antoine Picon mentions: *"It is strange to observe how the discourse on emergence has so far been monopolized by architects and architectural theorists although it applies in a more obvious way to landscape than to architecture."* [58]. The recognition of time for any landscape project is also mentioned by Hutton [2] were she adds maintenance as one of the key elements in the tectonic expression of terrain. This becomes apparent when we look at its

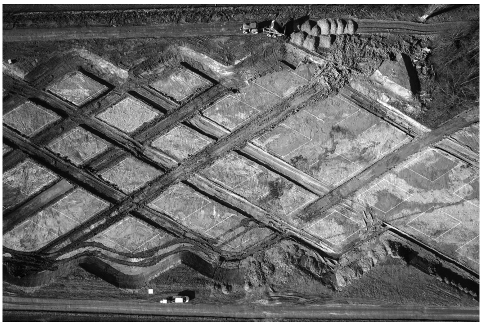


Figure 2.7: The River Aire project by Atelier Descombes Rampini during construction and pictured from above. The seemingly architectural form of the terrain evolves under the influence of flowing water into the *Renaturation of the River Aire* [56].

many time scales, ranging from geological time in the formation of continents up to rapid changes that occur in hazard events. As Barnett describes:

> *"Open systems ... [and] their components are connected by networks of feedback loops operating at different levels, different scales and different rhythms. Landscapes work like this. This is why it is not necessarily useful to think of them in terms of types. As complex adaptive systems their higher order patterns are the result of their continual interactions within and without, of their ongoing openness and responsiveness to quite specific, changing conditions. We should think of landscapes as generated by, and therefore imminent to, the specific conditions they comprise. How we remodel landscapes is a question how we gather and direct these forces and, indeed, this is just what gardening is: the production of difference through the husbandry of natural processes."—Barnett [59]*

When aspects of time and dynamic processes become more important for landscape architecture, the simulation and representation of it becomes a key design technique. While cartographic representations do include principles of formation when representing relief, it remains hard to understand how it came into being. Only through diagrams, superimpositions, sequences, animation, and experiments can we understand how it evolves or will evolve in the future. This is nicely illustrated in Figure 2.8, where the form of barchan dunes is never static nor final, but ever-changing by the flow effects of water.

2.2.3 Terrain as Substance

From the previous sections, we have seen that the processes in terrain are driven by solid and fluid states of matter. This Section will look at the substance of ter-

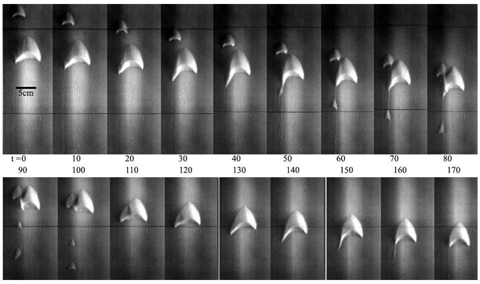


Figure 2.8: Flow effects on the morphological evolution of subaqueous barchan dunes by Hersen [60], in a continuous play of splits and mergers.

rain, its material make-up and how it characterizes landscape architectural design approaches.

Soil Texture and Profile

Terrain is made up of mostly mineral components. Its expression on the surface is determined by its internal rock structure. Here, three major types are distinguished by its formation process. An igneous rock (1) is formed from solidified magma or lava. From loose and granular particles sedimentary rock (2) is formed through lithification. And metamorphic rock (3) arises through physical and chemical transformation of existing rock material under the influence of high temperature and pressure. These processes continue endlessly in the so-called rock cycle. Due to these processes, every site has a particular structure and material mineral mixture, which has a direct influence on the ecological systems harbouring in it. This vertical dimension of the terrain is referred to as stratum, and makes for the load-bearing material and starting point of any landscape construction.

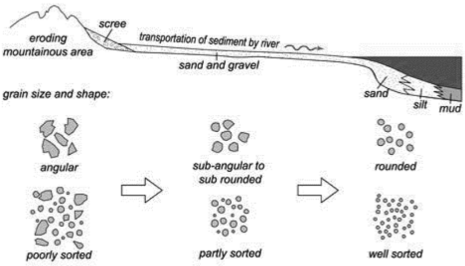


Figure 2.9: *Sediment Transportation and Sorting* [61] of grains resulting in various soil textures and profiles due to natural processes of erosion, transportation and sedimentation.

More close to the surface, these geological horizons can be looked at through the lens of its texture and its profile. Through weathering, erosion, and transport, rock particles break apart into a large spectrum of natural grain sizes and shapes. The shape—round or angular (see Figure 2.9)— and size has a direct effect on its mechanical behaviour. The material constitution of this regolith can be defined by its soil texture class that distinguished by its grain size. While the percentage of clay, silt, and sand determine the name for the soil. When mineral particles are mixed together with a large amount of organic material, we refer to this layer as soil or topsoil. This is the most precious layer since it provides the nutrients for all plant life. Most of the ecological impact can be traced back to disturbances in this layer, and more recently, soil has become scars [62].

THE MINERAL COMPONENT OF THE SOIL

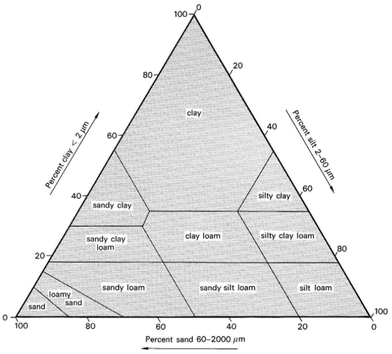


Figure 2.3. Triangular diagram of soil textural classes (after SSEW, 1974).

Figure 2.10: Triangular soil texture diagram displaying the mineral components of soil from White [63, p. 11]. By analysing the percentage of clay, silt, and sand in a soil sample, it can be classified using this diagram.

Resilient Terrain

Pedogenesis, how soil is formed under the influence of place, environment and history, is described by Lin [64] as the result of three principles: conservation and evolution, dissipation and organisation, and lastly space and time. By inputting energy and matter, the soil profile reacts, transforms and evolves into new material matrix[2], a new structure and a new form. This entropic process in soil has been closely linked to the broader landscape evolution of patterns and forms in one-to-one correspondence, though the evolution of soils and landforms have yet to be linked in quantitative modelling methods [66]. In short, the development of soils over time consumes energy and exports entropy through self-organisation. Its resilience depends on its ability to recover from shocks and disturbances back

---

[2] Soil consists of a solid phase of minerals and organic matter (the soil matrix), as well as a porous phase that holds gases (the soil atmosphere) and water (the soil solution) [65]

to an equilibrium state in terms of human expectations and time frames [67]. This resilience is further linked to the concept of resurgence in organic matter by plants and animals, the ability to recover multispecies assemblages on disturbed sites.

The form of terrain as a method for environmental remediation and ecological resilience traverses all space and time scales. Conceiving landforms as events amidst a field of forces, acknowledges its entropic and resurgent qualities, and a critical understanding of the balance between the two is essential for a resilient landscape practice. As Claghorn notes: *"Landforms which align with [processes of change in time] ... will endure for much longer, while landforms standing against such forces will be quickly eroded or disintegrated."* Claghorn [68].

Scales of Terrain

Scale has been acknowledged as a basic problem throughout the scientific studies relating to terrain. Terrain is not a homogeneous substance, it varies widely in particle size and chemical makeup. Its formative principles range from the smallest clay particles up to regional and even continental scales. The way terrain behaves and is analyzed changes drastically throughout these scales. In determining is mechanical properties, a clear understanding of its particle size, moisture level, and density is critical. This is not only true in slope stability (see Figure 2.11), but also in response to outside forces like water, where large boulders have a much better chance in withstanding erosion as the same mass would have as individual particles. Also in the categorization of landforms, scale plays a significant role. As scale in landform analysis is mostly a function of resolution, land surface parameters can have different values at the same location [69]. The race towards the highest resolution possible in digital elevation models as a quality signifier has mostly ended now that they are widely available. Higher levels of resolution may just as well represent higher levels of noise. Instead, scale optimization techniques remain the priority. As mentioned before (see Section 2.2.1), terrain behaves in the smaller scales as individual particles and at larger once as a solid surface. The human scale seems to sit right at this intersection, which has many implications for digital design and fabrication methods (see also Section 2.3).

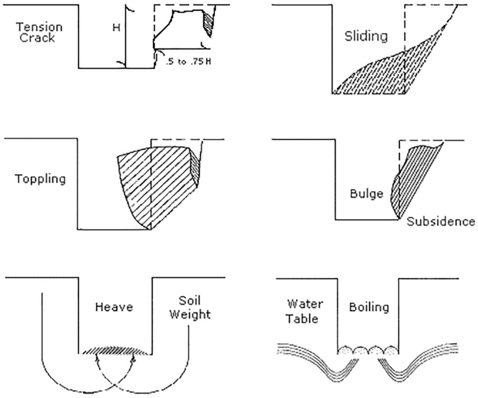


Figure 2.11: The *OSHA Technical Manual Section V: Chapter 2 - Excavations: Hazard Recognition in Trenching and Shoring* [70] defines the limits of soil stability in trenches based on their dimensions. Failure may occur as cracking, sliding, toppling, sinking, bulging, heaving or boiling in relation to the scale of the excavation and water content.

2.3 Instruments of Terrain

A typical workflow for a landscape architectural project today consists of the survey, the design, and the construction phase. In every phase, drawings or data flows from the one phase into the next. With the advent of the digital workflow, the gap between the survey, the design and the fabrication is closing. The robotic mechanism further integrates the link between the digital and the material world by a continues loop between found material (survey), modelling a response (design) and manipulating the material (fabrication), see also Section 1.2. The robotic mechanism changes the traditional workflow from a linear to a circular process where the survey, design and fabrication phases are explicitly linked together [71]. This makes the information exchange between the three phases particularly important. Followed below is an overview of the current stand and limitations of the instruments applied in each phase structured around models of information, models of design, and models of fabrication.

2.3.1 Models of Information

Instruments that Sense

The specificity of any site requires a thorough understanding of its form and processes. Before an informed action can take place, instruments help to measure its geometry and understand the dynamic processes on site. Triangulation, measuring a point from two separate locations, lies at the basis of all topographic surveys. Precision in topographic measurements, developed in 16th century in The Netherlands to make new land, and around the same time in France towards perspectival illusion, relied on the inventions like the telescope, the quadrant (see Figure 2.12) or graphometre [4, pp. 173–177]. Since then, many instruments and techniques that measure topography have been developed; from the theodolite to stereo pairs in aerial photography and since the early 1960s laser scanning. Digital surveying instruments and numerical methods have dramatically increased the speed at which the triangulation of a point can be achieved. Today, up to millions of points per second can be acquired using a wide variety of instruments. They range from terrestrial to aerial implementations up to satellites in space.

For topography, that is the bare surface of the earth, systems based on lasers are generally more beneficial to other methods in its ability to penetrate through vegetation more easily. For the same reason, aerial applications scan the terrain from an ideal perpendicular angle, while terrestrial scanning suffers from shadows thrown by objects or vegetation on the ground. Satellite surveying techniques, mostly radar-based, have yet to provide the resolution necessary for the scales of a landscapes architectural project. As a result, laser-based aerial systems are the most common but require a sizeable aerial platform to carry the instrument. More recently, driven by the automotive industry's goal for self-driving vehicles [72], laser scanning has become more ubiquitous and aligns itself elegantly with robotic construction machines through the shared use of lidar[3] scanners. The same technique can now be considered for the design, evaluation, and instruction phases as a shared point cloud base for autonomous robotic construction [12]. Because small and light laser scanners are becoming more available, it also makes them suitable for UAV applications (see also Section 3.2.1).

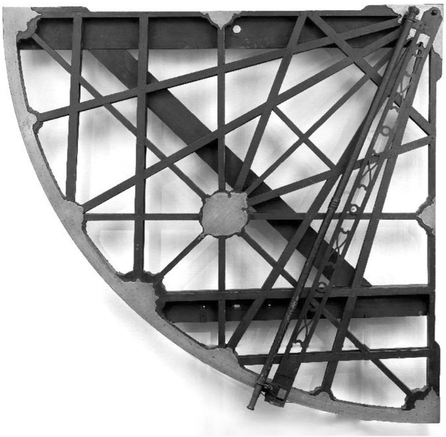


Figure 2.12: The *Quadrant of Snellius* [73] was developed in Holland for large-scale surveying around 1610, e.g. in a first attempt to measure the circumference of the earth by triangulating church spires over vast distances over the flat Dutch landscape.

With the advent of new, highly precise surveying techniques in the late 1990s in the form of lidar, the possibility of digital 3D modelling in terrain became possible also for the larger landscape scales. The point cloud model enabled a shift in precision and perception for the production of large landscapes and infrastructures. Since 2009 the Chair for Landscape Architecture of Christophe Girot has investigated point cloud technology in order to include all the physical and expressive properties of a given site. It tries to close the gap between two dominant paradigms in landscape representation, between a descriptive reading and the "gaze" [74]. Research on point cloud modelling as a representative and performative format for large-scale landscape architecture was concluded in 2016 by Lin [75], and others are ongoing. As the potential of surveying techniques for quantitative analysis may be clear, using instruments as a basis for qualitative research and design may not. While the survey instrument is becoming a critical tool for the development of a landscape project [76, pp. 56–67], there is a need

---

[3] The word lidar was first used in the 1960s as a combination of "light" and "radar". Now it is also used as an acronym for "light detection and ranging" or "laser imaging, detection, and ranging" and can be referred to as 3D laser scanning as well.

for a holistic view on quantitative analysis and its application in design-oriented modelling software. Here, the interpretation and application of survey data requires an understanding of how it was taken [77]. While a site may never exist in all its normative and poetic dimensions digitally, the attempt is worthwhile for the design process itself. A return to the physical reality of the terrain can therefore benefit from the development of instruments that reveal it [78].

Figure 2.13: Point cloud from a terrestrial laser scan of the forest in Sigirino, Tessin, before the material of the Ceneri Base Tunnel was deposited on this site, from Girot et al. [49].

Geographic Information Systems

The production of the landscape is increasingly based on the accumulation and intersection of large data scapes [58]. These include not only the visible form or processes in landscape, but include its invisible dimension on or below its surface [17]. Through sensing technologies, these can be made available for design. Geographic information systems (GIS) are widely used and particularly good at storing all the different attributes of a landscape. Every cell [4] can hold an endless amount of attributes, going far beyond formal aspects (like attributes such as curvature, aspect, gradient) of terrain. For example, attributes to soil types, granularity, and solid rock layers can be stored, as well as secondary information that is based on the relations between these attributes. Recent examples that measure terrain beyond its visible surface include multispectral camera's, ground-penetrating radar or the analysis of soil composition based on force feedback. As such, the survey has become not only a descriptive tool in relation to the natural world but one that is critically linked to the making of landscapes as well, encompassing many of the relations and superimpositions existing in natural and manufactured material systems.

---

[4] A cell is the smallest unit of information in raster data and represents a portion of the earth in a geographic information system.

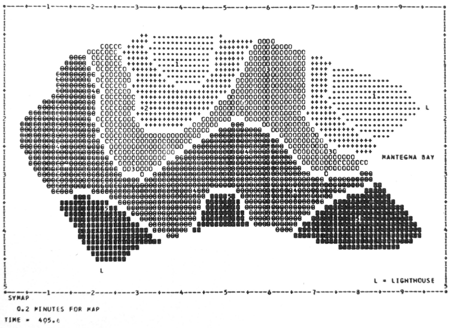


Figure 2.14: Example of a surface interpolation with SYMAP 3, one of the first digital geographical information systems developed among others by Carl Steinitz, from Waldheim [79].

The development of GIS in the 1960s was an attempt to store social and spatial data digitally (see Figure 2.14) [80]. Ian McHarg wrote the influential book entitled Design with Nature, which promoted ecological thinking to the domain of landscape architecture and had a big influence on the discipline, especially in North America [81]. The mapping techniques that are elaborated in his book categorizes landscape in separate topics of 2-dimensional layers. While the storage and analysis of survey data in a geographic information system is very efficient, designing with it is excruciatingly difficult [75, p. 16]. Computer-aided design software fills this gap by focussing on the free-form drawing of geometries. However, the lack of flexibility in GIS is equally reflected in the lack of attributes in cad systems. When designing with NURBS as curves or surfaces, the attribute model is mostly absent. The mesh format does allow for attribute storage, but only in specific cases relating mostly to its representation on a computer screen.

Even though advances in raw point cloud modelling have been made, the modelling of terrain-points still relies on conventional techniques before they can be visualised in the original point cloud. As it stands, raw point cloud modelling does not offer a benefit over existing terrain modelling methods. The point cloud model, being closely linked to GIS, does allow for attribute storage, with the added benefit of encompassing 3D space in full (as opposed to the original attribute model in GIS). Based on point cloud technology and recent innovations in cartography, 3D GIS applications are becoming more available. The benefit of encompassing the physical reality as a whole is especially crucial in spatial and aesthetic digital experiences. Since it is unlikely that natural granular material forms terrain overhangs or caves, a 2.5D representation of terrain as a surface suffices. A particular case is the makeup of terrain itself in terms of its soil profile. Here, volumetric modelling techniques show promising applications.

2.3.2 Models of Design

Digital design systems form the ideal environment to leverage the abilities of a robotic fabrication platform due to their ability to connect to both surveying and fabrication equipment. However, at the moment there does not exist a single solution that is capable of both free-form modelling and management of these data flows. While designers mostly prefer the use of a graphical user interface (GUI), working with robotic technologies today demand scripting capabilities. As both methods have their strengths and weaknesses, this Section will discuss current models used in designing terrain structures.

Explicit and/or Implicit Modelling

While innovations in surveying instruments have opened up the digital recording of large-scale topographies in detail, digital terrain modelling is still a complicated and time-consuming task. The geometry of the ground with all its irregularities and chaotic nature poses severe problems for a streamlined digital workflow. Maybe because of this, the practice of landscape architecture is only slowly implementing 3D modelling techniques compared to architectural practices. Landscape architecture, being a relatively small discipline, always had to borrow software solutions from other disciplines to draw and model terrain. They usually come from architectural or industrial design. In these free-form modelling environments, geometry is encoded as a boundary representation (BReps) with either NURBS or meshes. The digital equivalent of terrain modelling is best described as Boolean operations, but these tend to be problematic on large-scale meshes, quickly reaching the limit of the CAD software. Terrain being unstructured and irregular in shape, it is difficult to efficiently encode its topography as a NURBS surface without losing too much detail. A typical workflow for design in terrain therefore often involves the trimming of a larger mesh, and filling this hole with a newly designed NURBS surface.

While free-form cad software mostly relies on boundary representations (explicit modelling), geometry can also be encoded implicitly relying purely on arithmetics. This method, also known as volumetric modelling, has become popular due to 3D printing techniques where a boundary representation does not exploit a full spatial description [82]. The visualization can also be disconnected from the 3D modelling itself, increasing performance and flexibility. This technique can be applied to terrain data as well, while retaining (some of) the benefits of free-form modelling tools. A full description, new developments and discussion is presented in Chapter 3.

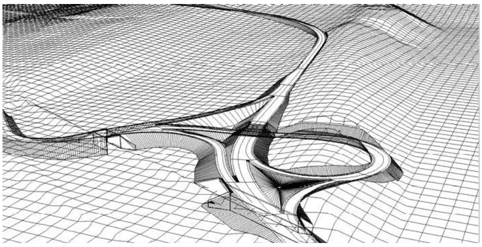


Figure 2.15: The difficulty of modelling terrain using meshes is visible in this road modelling example where a base rectangular mesh network is supplemented with a triangulation of the curves of the road with subsequent mesh Boolean operations, from Ljutić and Babić [83].

Intuitive and/or Precise

Intuitive modelling techniques in terrain have been—and still are— an important phase in the design of landscape architectural projects. Plastic models are easy to form by hand and spatial relationship instinctively comprehended [84, pp. 155–163]. Digital equivalents exist in sculpting tools like Z-Brush or Mudbox, and visual validation can be implemented in virtual or augmented reality applications. Also, physical interfaces to digital and intuitive modelling tools have been developed like the haptic devices from 3D systems [85]. By linking the plastic model to sensing technology, physical design interfaces have shown a great potential as design tools. To aid the landscape designer with the modelling and drawing of landscape topologies, various physical/digital design systems have sprung up over the last two decades. Going beyond the pencil and digital drawing boards, these new interfaces combine the physical world with the analytical power of the computer. Research projects like "Illuminating Clay" and "Sandscape" [86] by MIT Media Lab, show how designers can transform digital information through working with media like clay and sand. The users sculpt with their hands in a sandbox while a scanner translates the data for analysis before projecting information back onto the sand. At the Chair of Landscape Architecture ETH Zurich, both photogrammetric and real-time scanning solutions have been applied in teaching in 2012 and 2014, see Figure 2.16. The Setup contained a sandbox, a Kinect scanner and a computer screen where students could see in real-time how their topologies influenced flooding events [87, p. 401]. The goal of these design tools is to close the gap between the designer and the physical reality of a landscape in all its complexity in form and process. However, these intuitive hand tools lack the precision needed for construction. This means that after this intuitive phase, the sandbox has to be re-modelled digitally using conventional modelling tools.

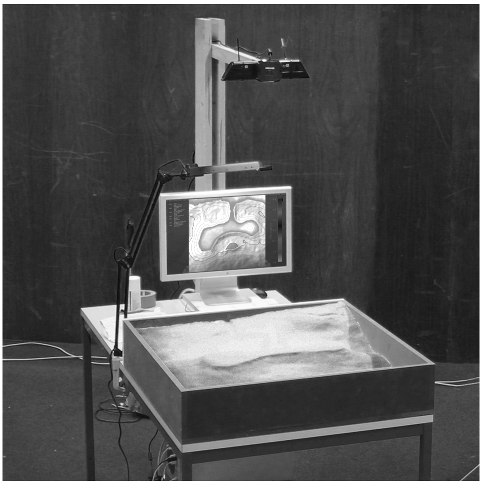


Figure 2.16: Intuitive terrain modelling interface, where the real sand in the sandbox is scanned and analysed using a 3D scanner. The screen above the sandbox displays the analysis in real time to the designer, from Hurkxkens and Munkel [87].

The (In-) Flexibility of Parametricism

In free-form digital modelling, geometry is manipulated directly using a computer interface like a mouse or by encoding its coordinates directly. Using manual inputs, a model is made step by step without control over its previous steps. In opposition, parametric modelling techniques define geometry as a set of dimensions that generate a shape. This means that at any point in time, the model can be re-generated using a different set of dimensions. Depending on how the parametric model is built, a combination of free-form and parametric modelling is possible by linking the parametric model to the manually drawn *design curves*. Greg Lynn formulates the power of parametricism for design as follows: *"...the most interesting thing about parametrics [...] is the ability to fuse the hierarchy of parts and whole to produce a deeply modulated whole as well as infinitesimal variation among parts."* [88, p. 92]. Parametric modelling is widely used throughout engineering and construction and often implemented as building information modelling (BIM). However, it is hard to change and adjust individual components, and building a parametric model that accommodates this is difficult and time-consuming (as opposed to free-form modelling, where this is trivial). Parametric modelling has become linked to graphical user interfaces or visual programming (see Figure 2.17), though it can just as well be applied as code alone. As such, it also allows the customization of modelling tools, which is aligned to the revival of bespoke manufacturing that has become economically viable again using digital fabrication [89]. One of the critiques of parametric modelling is that it favours a particular design language or style, not unlike the fractal patterns we find in nature by the repetition of a simple process over and over again. This is partly due to the fact that it is straightforward to create recursive patterns using algorithms. However, the critique on a parametric modelling style should not be mistaken with its underlying power that separates the (topographic) dimension value from the (topological) description of a shape (see also Section 5.2.2).

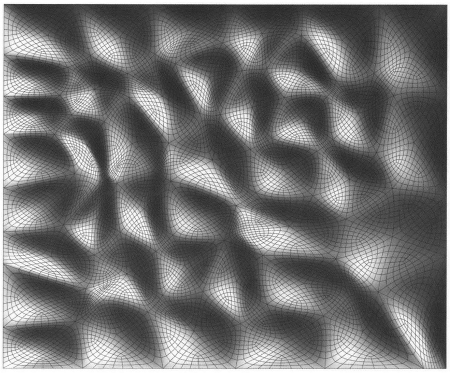


Figure 2.17: Parametric voronoi surface structure generated solely by algorithms using the graphical programming interface Grasshopper within the free from modelling environment of Rhino 3D, from Tedeschi [90].

Computational Modelling

Most structural testing today involves statistical and numerical methods that depend on computation. Here, models are not as much representations of static form as of dynamic processes [91]. Computation can help produce complex designs and evaluations that are otherwise impossible to achieve. But apart from automation (things that can also be done manually) and simulation (things that also exist in the real world), computation as a digital technology is an expressive medium in its own right. When talking specifically about *designing* digital terrain surfaces, the tools and techniques of this medium have rarely been explored. One prototypical case that stands out is the Topographic Surface Sculptor [32], where a graphical user interface follows the process of creative sculpting using a system of symbols and actions (see also Section 3.3.2). The recent focus on performance—over a romanticised view on the landscape—makes computational design methods indispensable. In this light Cantrell and Mekies [92] mention: *"Computational thinking combines the powerful orderly process of algorithmic organisation with the equally powerful, but more chaotic, process of iterative design."*. As such, computational models allow designers to study and experiment with dynamic systems where intuitive analytical solutions are simply not available.

Design Constraints

To leverage computation as a design driver, modelling of construction constraints offers a powerful methodology. Over the last two decades, design constraints have become a popular digital design tool because they can define a full solution space to a problem. This has driven innovation by presenting "computable" design solutions that were "unthinkable" before. Decision making in the synthesis of form has been rationalized as a relational program already in the 1960s by Christopher Alexander. He argues that formal clarity cannot exist without functional clarity, and that design is the process of finding a good fit between the two [19, p. 15]. His "program" decomposes the problem into subsystems and their relations. This hierarchical problem description will then lead to a new design as its structural components clarify the form's physical shape and organization (see also Section 5.2.2 on how this relates to topology). However, the circular nature of design processes (see Section 5.2.1) requires both top-down and bottom-up constraints descriptions. Kilian [93] argues that a truly supportive design exploration using constraints need to be bidirectional and should not only be implemented as a hierarchical structure where effects only propagate from the higher to the lower levels. Kilian distinguishes three types of bidirectional constraints: (1) branching, to establishing constraints for an undefined design problem; (2) circular, to refine constraints relationships; and (3) parallel, for well-understood constraints (for instance in form-finding algorithms). For any design, specific constraints can be defined between any component. In digital fabrication, they mostly relate to material constraints, construction system constraints, and machine constraints. However, constraints can be set up as formal properties as well through using landscape topological methods, which define aspects of context, function, and performance but also artistic expression or other cultural dimensions. Section 6.2.1 summarizes the constraints from the research experiments in Chapter 4 and 5 for dynamic design and formation in terrain.

2.3.3 Models of Fabrication

The development of heavy construction equipment has always followed and propelled large infrastructural projects of its time. While many fundamental mechanical principles for earth-moving were established over many centuries using horse or ox-drawn equipment, at the turn of the 19th century, it was the need for greater and more reliable power in the construction of canals and ports that propelled steam as the power source for heavy equipment at the time [94]. Towards the end of the 19th century, railroad construction took over as the main construction project which drove the use of hydraulic cylinders, motorized power and on-board operation. With the increasing availability of cars in the 1920's the demand for roads propelled earth-moving equipment to become even larger and more powerful. Many more specialized but also versatile machines came on the market, and the construction boom after World War II saw hydraulics replace cables as a means of equipment control [37, p. 4]. The ever increasing demand in earth's natural resources has since introduced many more innovations in automation, leading towards fully autonomous equipment used in mining today. The main infrastructural project for the coming decades may well be aligned to the effects of climate change. This poses new questions for a sustainable earth-moving practice in light of ecological resilience. As a way forward, this section will discuss robotic construction equipment as a technology that is well-positioned to take up this challenge.

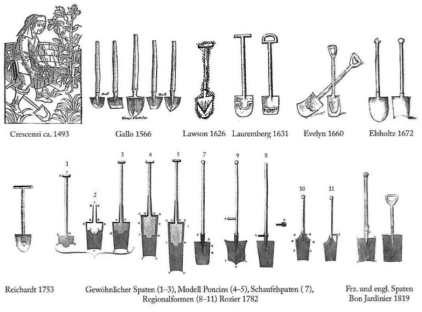


Figure 2.18: Manual earth moving tools: the form of spades from the 15th to the 19th century (source unknown).

Autonomous Equipment

The evolution from hand tools to fully autonomous excavation equipment is still ongoing. Starting with the adoption of steam power, the invention of hydraulic equipment revolutionised what was possible in terrain. Tractors, dozers, excavators, loader, trucks and scrapers all rely on this fluid power. However, as a tool, the shovel or the bucket has not changed much over time. The way loose and granular material is manipulated by the end-effector[5] seems to be one of the stable factors in earth-moving practices. The way its movements can be controlled using robotic systems can revolutionise how a landscape is made. This is made possible through the application of advanced mapping, localisation, adaptive control, and on-line communication on heavy construction equipment [95].

Current on-site robotic construction methods for landscape architecture are mainly focused on planning and horizontal grading [96, p. 205] through the optimisation of material flow using GIS guiding systems. While these advances

---

[5] An end effector is an accessory that is attached to the end of the (robotic) arm and is the part that is in contact with the terrain.

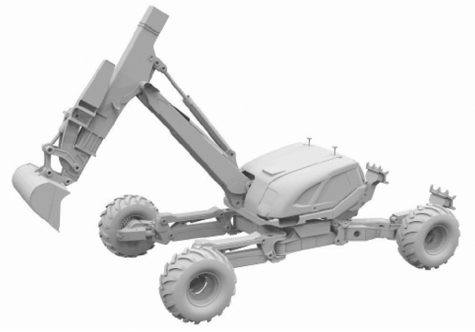


Figure 2.19: Illustration of HEAP (Hydraulic Excavator for Autonomous Purposes) without on-board control and cabin where a human operator would normally reside.

in automation and precision are significant, they do not address the specific intelligence of a project using the design potential of robotic construction methods in landscape architecture (see for example the paperless and stake-less grading of ASPECT Studios' Victorian Desalination Plant and Snøhetta's Max Lab IV project [97, p. 160]). It may be evident that new robotic technologies will shape the future of the landscape architectural profession. Komatsu, the world's second-largest construction company from Japan, has announced the development of robotic bulldozers and excavators in 2015 [72], and an American start-up already delivers an add-on system for hydraulic machines [98]. Three basic systems can be classified; those based on a human operator, those that include guided systems and those that are fully autonomous. Automating the process of excavation has been researched from the early 1990s. However, most of these approaches tried to follow a position trajectory to perform the excavation. Due to the varying ground properties, various techniques using impedance control and learning algorithms yielded limited results in precision and soil estimation. The robotic platform THOR by Schmidt, Proetzsch, and Berns [99] and LUCIE by Bradley and Seward [100] uses behaviour-based control following position trajectories. Soil estimation systems were tested by Zhang and Singh [101] and Luengo, Singh, and Cannon [102] modelled the resistance of the soil in order to optimize the digging cycles. The Robotic Systems Lab at the ETH has taken a new approach by defining a single digging cycle as an interaction force trajectory of the end effector. Here, a walking excavator (depicted in Figure 2.19) is fitted with force sensors and promising results have been demonstrated [103, p. 613]. Especially of interest to landscape architecture is the ability for adaptive control depending on formal and material composition, and progress towards this goal has been made within the scope of this research (see also Section 4.4).

Craftsmanship

Large soil movements and reconfiguration of natural systems have left a significant imprint on natural and cultural habitat. With the advent of hydraulic earthmoving equipment, the underlying form of the landscape has lost its power to influence the way large-scale infrastructure projects are embedded in terrain. The value and constraint of handcraft in contemporary earthworks do not play a role any more. A careful manual assembly has been replaced by mechanical and digital interfaces that steer large hydraulic equipment. This led to a separation of design and construction and increases the distance of the designer to its physical manifestation. Through the application of digital fabrication techniques, this lost manual craft can be recovered by a digital craft in the manipulation of material with robots [104], and as a result, it can bring the designer back to the terrain itself [105]. The search for objective design through computational methods in digital fabrication drives its ability to reinvent, but it is permeated by this contradictory nostalgic force as well. In landscape this is particularly apparent, where one often looks for a long lost connection between the material world and ourselves [106]. In the poetic case, one of the potentials of digital fabrication is seen in its ability to imitate natural formation. But as a new technique and practice, its potential is much more disruptive and forward-looking. Brian Arthur formulates this dualism nicely: *"Our deepest hope as humans lies in technology; but our deepest trust lies in nature. These forces are like tectonic plates grinding inexorably into each other in one long, slow collision."* [14]. It is still unclear whether this dialectic remains valuable in the future, though many argue against this opposition (see also Section 2.2.2). The next Section will discuss computation as a way to break down the barriers between digital and physical worlds in design.

Material and Machine Computation

The convergence of the digital and the material in design and construction, enabled through innovation in sensing technology, computation and robotic control, has been denoted as *digital materiality* [104] or as *material computation* [107] [108]. Here, the robotic design- and fabrication process manipulates and is informed by the material behaviour. Because both physical material as a substance, and digital material as information compute and process, there is a confusion between a natural "found" computation in the physical world, and an artificial "designed" computation in a digital environment. We can distinguish between the two as machine computation versus material computation as defined by Dierichs and Menges [107]. A good example of material computation are the form-finding experiments of Frei Otto in sand [109]. Here, the form is the result of the interaction forces in the sand under the influence of gravity (see Figure 2.20). The potential of material and machine computation in granular systems is formulated by Dierichs:

> *"In combination, these two informational streams of material and machine computation allow for a more profound view of a specific aggregate than either in separation. Further research can be conducted into the relevance of material computational models not only on a practical but also on a design methodological and design theoretical level. The information process lying at the core of these computational models will then not only be perceived as being relevant on an applied level, but also give rise to new design procedures and theoretical approaches." Dierichs and Menges [107].*

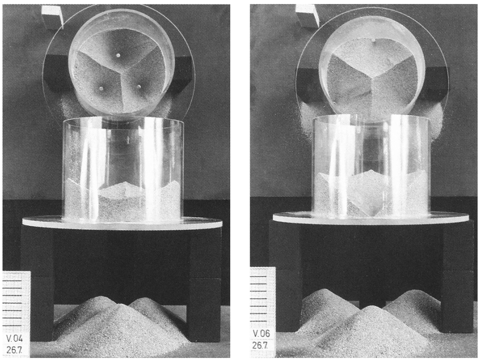


Figure 2.20: Frei Otto's sand experiments from the early 1990's that explore the natural formation of granular material in crater and scree cones, from Bayern and Stuck [109].

The potential of self-organisation and the ability to steer natural processes as they evolve leeds to a new design paradigm [110]. In the project Procedural Landscapes, Gramazio Kohler Research in collaboration with Christophe Girot, Chair of Landscape Architecture and Yael Ifrah carried out an experiment of this concept in relation to landscape architecture [111]. This elective course at the ETH Zurich explored the processing of shapeless sandy materials through digitally controlled machines equipped with sensors that allowed the students to implement feedback-driven formation processes into their landscape designs:

> *"This indeterminacy, which presents a special challenge to the designer, can be addressed by sensor technology, which is used to capture the morphological traits of the emerging formations after each single fabrication step, allowing the system to react to these in real-time. That means the next steps can be adjusted and calibrated in such a way that the amount, position and drop height of the deposited sand correspond to the changed situation. [...] The result is the blurring of the formerly sharp borders between data and material, between form and structure, between the design intent and the inherent behaviour of materials. Procedural Landscapes depicts an "in-between" in which the reciprocal effect of both worlds - the immateriality of the digital and the materiality of the physical - mutually*

> *strengthen one another." Gramazio, Kohler, and Willmann [110]*

These processes were simulated in model-scale using small-scale robotic arms (see Figure 2.21). Although the computational techniques as a new method in the design of granular material were established here, the application for large-scale landscape design were not studied. This research will continue the study of reflexive design methods and applications for robotic earth-moving as described in Chapter 4 and Chapter 5.

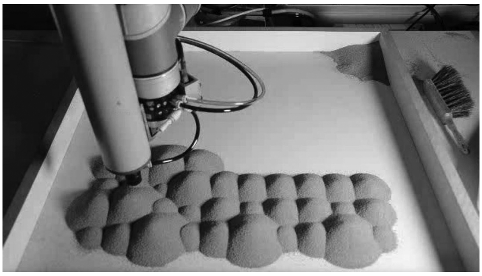


Figure 2.21: The *Procedural Landscapes* [111] 2011 elective course by Gramazio Kohler Research in collaboration with Professor Christophe Girot and Yael Ifrah explored the processing of sand through digitally controlled machines equipped with sensors to allow for feedback-driven formation processes for experimental landscape designs.

Dynamic Fabrication in Granular Material

Aside from earth-moving equipment based on automation, truly dynamic fabrication has yet to be explored in landscape architecture. As a dynamic fabrication approach in loose and granular material is still a novel concept, computational design and fabrication methods have only been studied in scale models. Apart from the Procedural Landscapes project discussed in Section 2.3.3, another example stems from the work of the Landscape Morphologies Lab on the Owens Lake. Here, a system comprising a robotic sand modeller, a 3D scanner, image projection and a design interface was used to exploring dust mitigation techniques. The formation could then be interpreted formally and on its performance using various analysis techniques [97, p. 132]. Another example stems from the Responsive Environments and Artifacts Lab, a graduate design thesis advised by Bradley Cantrell at Harvard. It used a geomorphological model setup that studied the fluid effects on granular material. Through real-time sensing and responsive manipulations, iterative adjustments were made to attune natural processes of erosion and attenuation. In one of the experiments, information from the physical model was linked to the deposition of sand to interrupt and steer the water (see Figure 2.22). More recently, Bar-Sinai, Shaked, and Sprecher [112] presented a method for shaping ground of remote sites. The experiments show the potential for robotic earth-moving where material and information flows are inherently linked through sensors. It opens up site-specific modelling by implementing local differences while informing the overall shape with the larger landscape morphology.

Figure 2.22: Sandbox experiment in the creation of a dynamic response to natural processes. Using a digitally controlled funnel, the amount and location of sand deposition is informed by erosion processes due to the flow of water in the sandbox, by student Estrada [113], advised by Bradley Cantrell.

2.4 Summary

The shift towards performance and materials over a formal approach in landscape architecture contributes to—and is accelerated by—the development of computational tools. It is grounded in the belief that technology is able to mediate an ever-increasing public demand on the landscape with prospering ecological systems. Through the combination of robotic technologies and computational tools, a new digital materiality is established. Here, focus lies not foremost on form, but rather is occupied with the flows and transformation of material and the processes of making, in opposition to the hylomorphic model [34]. As both processes in terrain and processes in robotic systems are inherently dynamic, combining these two forces seems only opportune.

The focus on the form of terrain as a design approach has long been approached as an aesthetic question in the landscape architectural discipline. Experiments from Frei Otto teach us that form is a direct result of the forces acting on it. In terrain, the underlying form directs the evolution of a landscape. This dissertation also understands this underlying form as a load-bearing structure for civilisation, and extends its aesthetic dimension with one of performance. Form not only gives value to the inherent beauty of a site but can provide resilience as well. In light of the ever-increasing superimposition of landscape systems and materials [50], the dichotomy between artificial and natural form and substance seems obsolete [2]. Instead, the expression of form should be evaluated on its aesthetics and on its performance as two independent entities while searching for a fitting symbioses.

A rational synthesis of form can benefit from a constraint description where all aspects of a project come together. Through models of information, design and fabrication, a close connection to the terrain and its formative principles can be established. A renewed understanding of made landforms—in light of topological modelling techniques—can re-imagine terrain in all its symbolic and poetic dimension, going beyond a mere empirical approach. As current digital terrain modelling tools are cumbersome and time-consuming, new dynamic modelling methods will have to be developed in order to leverage the potential of computation and digital fabrication. In turn, it can provide a reflexive design paradigm where processes of making are inherently linked to natural processes in the landscape.

Having described the state of the art of terrain instruments, new modelling tools (Chapter 3), dynamic formation strategies (Chapter 4), and design methods (Chapter 5) are presented in the following chapters arguing for robotic landscape fabrication as a method in the mediation of natural and cultural terrains leading towards a resilient landscape future. Maybe this way, the organisation of the environment allows for regeneration and resurgence in ecological systems while creating a safe and purposeful landscape structure for people. In his study of the Mont Blanc, Viollet-le-Duc [25] traces the origins of natural terrain to an ideal crystalline system (see Figure 2.23). Just like crystalline rock breaks down from high mountains peaks and turns into a loose and granular material, so does architectonic form under the influence of natural processes in terrain. At a distance a seemingly solid surface, up close terrain is nothing but a fluid cloud of particles. The poetic dimension of sand, gravel and rock is found between structured and unstructured material events. It is the task of the landscape architect to create a meaningful and performative language between the form of crystals and the formlessness of clouds.

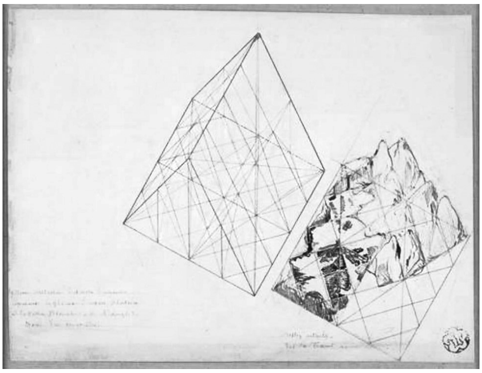


Figure 2.23: Rhombohedral system of the Mont Blanc. On the right the current remnants, while the left display the ideal crystalline form of the system, by Viollet-le-Duc [114].

Chapter 3

Encoding Terrain

"The objective in this case is not to mimic sculpting and modelling as we experience them in the real world [...], or to automate known manual methods [...], but rather to develop a system of symbols and actions that afford new ways of representing sculpting surfaces that only the digital environment may host."

—Caroline Westort [32, p. 9]

3.1 Overview

This Chapter covers the developments made in surveying techniques and digital modelling methods. As outlined in chapter 2, these developments are necessary in order to make terrain data available for a digital design and construction workflow. While digital terrain modelling has been in development for over 40 years, in most cases the focus is either on procedural terrains for application in games or films or towards analysis and simulation of the existing topography. As designing with topographic surfaces for landscape construction calls for both intuitive and precise methods, converging CAD with the attribute model of GIS may provide the necessary tools to come to an integrated design model. Central to the development of the terrain modelling tools in this Chapter is keeping a consistent data structure throughout survey, design and fabrication processes. This means that modelling techniques in meshes or NURBS had to be replaced using implicit methods that operate directly on a raster DTM. This was made possible with the help of Mathias Bernhard from Digital Building Technologies of Prof. Benjamin Dillenburger at the ETH Zurich, who was instrumental to the translation of volumetric modelling methods aimed at 3D printing architectural structures to a 2.5D application in a digital terrain model.

This Chapter starts with outlining a new aerial platform for terrain acquisition that was developed in collaboration with Dominic Jud from the Robotic Systems Lab (RSL) of Marco Hutter at the ETH Zurich. It continues discussing the data structure of a DTM, and how it can serve dynamic processes throughout preparation, design and execution phases. The fundamentals of implicit modelling methods are outlined and how they translate to distance functions for digital terrain modelling. Finally, it covers the development of Docofossor, a new terrain modelling plugin for Grasshopper of Rhino 3D that was developed within the scope of this research. This leads to new computational terrain modelling methods that form the basis for the design experiments outlines in Chapter 5 and the free-from autonomous creation of an embankment prototype with heap as presented in Section 4.4. As such, the work in this Chapter aims to aid robotic construction in terrain and digital terrain modelling in general.

3.2 Surveying Terrain

For any landscape design and construction project, having access to a digital terrain model is essential. While many administrative efforts are made to make this data available to construction projects, elevation data often does not have the required resolution or is outdated. In robotic construction, a regularly update elevation map is essential to be able to respond dynamically to changing site conditions, evokes either by natural processes or by the construction process itself. Because of these reasons, this thesis implements a lightweight UAV drone and has developed a lidar system in collaboration with the RSL, ETH Zurich. The following paragraphs will explain how topographic and other attributes can be acquired and processed to make it available for computational design and robotic construction.

3.2.1 Acquisition Instruments

Figure 3.1: Acquisition of a point cloud in Bondo, Grisons using the terrestrial laser scanner Riegl VZ-1000. Photo by Fujan Fahmi.

Data Sources

A design and fabrication process in terrain consists of a preparation and execution phase (see Section 4.4 and 5.3.2. While the execution phase relies on a regularly updated terrain map, for the preparation phase, a single map suffices to set the initial design constraints. In this thesis, the use of open-source data sets is combined with laser scans taken on site. The point cloud offers not only a precise digital terrain model, but functions as well as a representative format in the design and presentation of a landscape project [75]. In various design phases, the point cloud format was used for performance analysis and for presentation and visual validation of design interventions. The point cloud depicted in Figure 3.2 was capture using a Riegl VZ-1000 terrestrial laser scanner. The terrain but also the vegetation and buildings are therefore available for a digital workflow. Before one can start to model the terrain, it needs to be filtered to strip it from all vegetation, buildings and other artefacts. After registration and segmentation in the RiScan software package, CloudCompare was used to merge and filter the point cloud to achieve a workable DTM (see for example Figure 3.7 that shows the bare topographic data form an aerial laser scan by *swisstopo* of the Gürbe River in Canton Bern). The segmentation, filtering and rasterizing of a point cloud into a digital terrain model is a destructive process where data is lost. Going back and forth between a full resolution point cloud model and a DTM is therefore not possible. In the design experiments of Chapter 5 both the full point cloud and the bare DTM lived side by side in the digital modelling environment.

Figure 3.2: Full colour three dimensional point cloud from the terrestrial laser scan of the detention basin for the debris flows in Bondo, Grison.

Lidar UAV

Since the acquisition of large point cloud data sets using terrestrial (see Figure 3.1) or aerial laser scans with planes or helicopters is a time consuming and laborious process, it is only feasible to do it a few times during a projects lifetime.

For this reason, photogrammetric methods using small drones have seen many applications that require monthly or even daily updates, for instance in open-pit mines or agricultural applications [115]. While this method is straightforward and quick, photogrammetry is unlikely to capture correct terrain data in the presence of dense vegetation. In this case, lidar is more suitable, especially since small and cost-effective lidar systems, driven by the recent focus on autonomous navigation in the car industry, have made them available for lightweight UAV applications. Because the scale of earth-moving operations is linked to the scale of the machine, the range and resolution of the terrain data does not have to extend far beyond the machine's immediate surroundings during execution. However, vision sensors on the machine itself cannot see behind topographic features or objects on site. Because of this, terrain recognition can benefit from an aerial system that can inform the terrain map for future operations and for preparation purposes. In light of these constraints, a lidar UAV was developed in collaboration with Dominic Jud of the RSL[1].

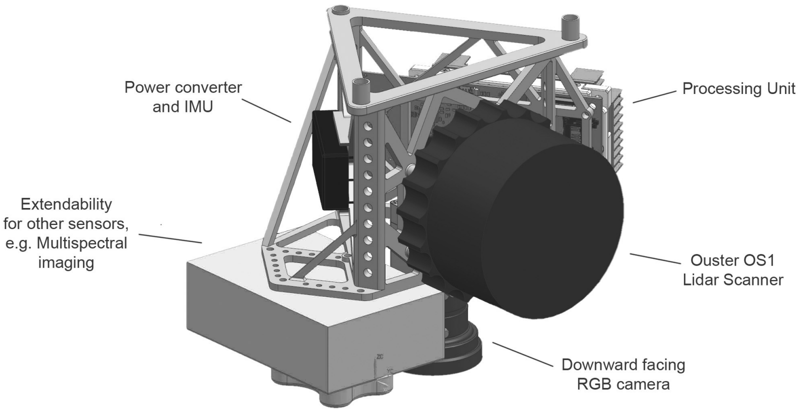


Figure 3.3: Design drawing of the flexible lidar system with on-board systems and mounting brackets to attach it to the aerial platform. Figure by Fabian Grigis.

The goal of the hardware setup for the lidar UAV is to enable a flexible package where additional sensors can be mounted and integrated. An Ouster OS-1-54 with a range of 120 meters, a field of view of 31.6 degrees, and a resolution of 64 x 2048 points was chosen because it is the lightest lidar sensor on the market today[2]. An RGB camera and Multispectral camera is integrated as well. For the computer, a Nvidea Jetson is used because of its small package and little power consumption. It is using a DJI Matrice 210 RTK as the flying platform enables precise flight and geo-coordinates due to its real-time kinematics (RTK) capabili-

---

[1] Robotic Systems Lab, Prf. Marco Hutter ETH Zurich with the support of students Samuel Zimmermann and Fabian Grigis as their semester thesis project

[2] At the time of development, fall 2017.

ties. An inertial measurement unit (IMU) is integrated as well to be able to access state estimation for localization. Choosing this particular drone had the benefit of running power directly from the flight batteries. In total the setup came in just over one kilogram, which is very light for an aerial lidar system. On the software side, the robot operating system (ROS) provides the communication and operation of the various sensors. In Section 4.4 the drone was implemented to capture various stages of the robotic earth-moving experiment.

Figure 3.4: Lidar UAV in flight. Implementation of the aerial laser scanner with the lidar system mounted on the front.

The mapping and localisation algorithms are not fully developed at this time of writing. Instead of processing the data on-board, that would enable live-streaming of the elevation map from the drone to the design system, an offline solution is used. It is implemented using Google Cartographer, a system that provides simultaneous localisation and mapping (SLAM) in 3D. However, the flexible lidar system can eventually provide real-time solution as well. In Figure 3.5 a complete data set is visualised including vegetation, buildings and street poles. Through offline segmentation and filtering using the open-source CloudCompare software, a regular grid DTM is created with a 5cm resolution. The aim is to streamline this process further in the future and make it more robust and automated, though this goes beyond the scope of this research. Localisation was achieved by translating the Swiss terrestrial reference system (CHTRS95) to a local coordinate system by setting a new 0-coordinate in the field.

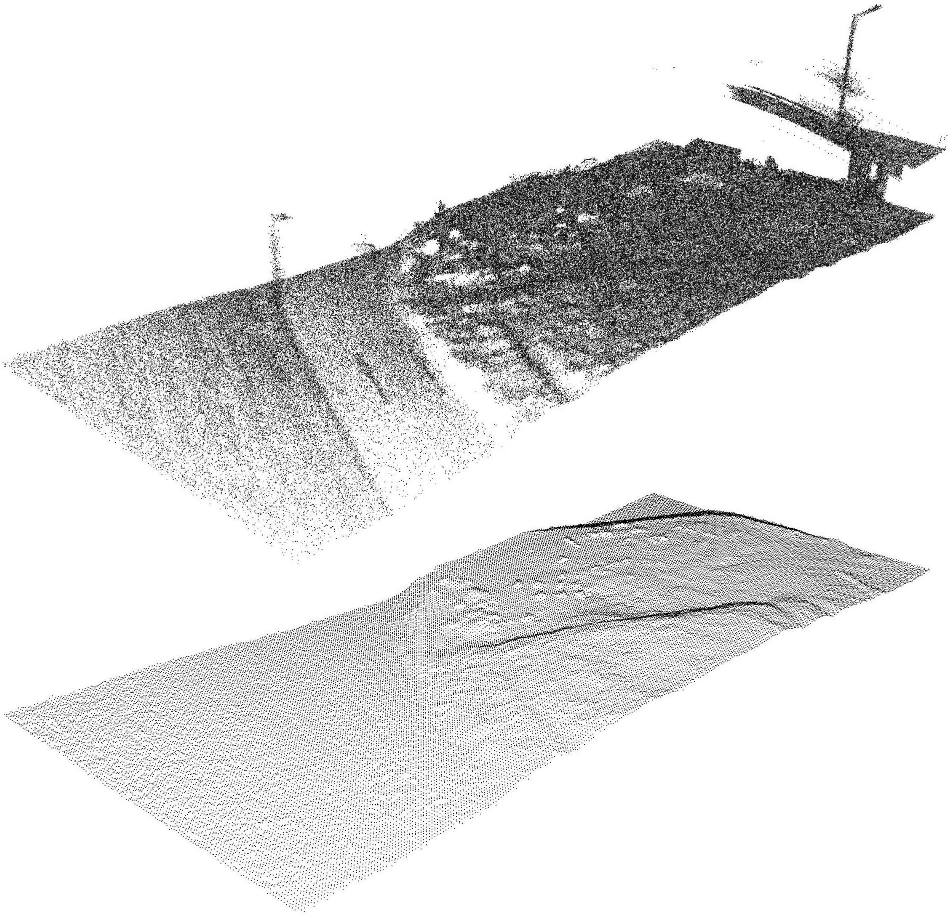


Figure 3.5: Resulting point cloud including vegetation and artefacts (top) and filtered raster DTM (bottom) from a flight of the aerial lidar system at the ETH test site.

Model-Scale 3D Scanning

Just as the survey plays an important role for the real scale experiments of this research, the model-scale experiments in the sandbox described in Chapter 4 also require the iterative scanning of the sandbox in order to formulate a robotic response. At first the Microsoft Kinect and later the Intel Realsense 3D scanners were used. Using the python wrappers for the Intel RealSense camera, the data was captured, segmented and filtered into a regular grid (see Section 3.2.2) before it was sent to rhino and rendered as a Docofossor mesh (see also Section 3.4.2). Here, localisation was achieved by applying the coordinate space of the robotic arm to the point coordinates of the 3D scan. This proved to be very effective, as the virtual and robotic operations could be directly related to changes in the sandbox.

3.2.2 Data Structure

The digital representation of terrain in a digital terrain model has many types of data structures depending on the survey instrument (like lidar or photogrammetry). There exist point-based, triangle-based, grid-based or hybrid approaches to terrain encoding and modelling [116]. The modelling of a digital terrain model can be achieved by direct construction from the measured data, or by indirect construction through the application of filters and interpolation algorithms.

Primary Grid Formats

In general, all the terrain data starts out as an irregular grid from the survey, and can be represented as a regular grid in a second step. On top of this, projection systems determine the actual x, y, and z values that are saved in the matrix (latitude, longitude, and height). The projection information is often saved in a separate file, or as a header information. Irregular grids use point values x, y, z and sometimes also additional data like colour r, g, b, nir, or GPS time information (usually from Lidar data). We can refer to this type as vectors or TIN (triangulated irregular network). A typical point file with xyz values will look similar to this:

```
610158.757   126828.809   785.045
610163.757   126828.809   784.766
610168.757   126828.809   784.487
...
```

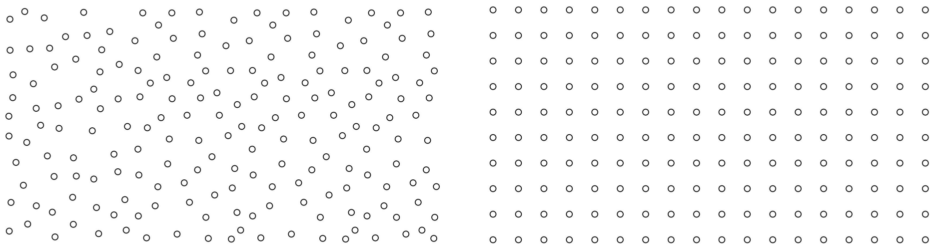


Figure 3.6: Illustration of two different grid types used for digital terrain models. On the left a vector based triangular irregular network (TIN) and on the right a raster grid of squares where the cells are represented as grid-center-points.

Secondary Grid Formats

Irregular networks can be translated into regular grids. Here, all data values fall into a grid with regular distances between x and y axis. This type of structure allows for smaller data files because the x and y values do not have to be stored along with their z value or additional attributes like colour information. It also has the advantage of layering data easily because every grid cell can have multiple attribute-layers attached to it. To know where the data is located in space, header information is necessary and contains the number of rows and columns, the origin of the data and cell size. A widely used and open ESRI ASCII Raster format. It looks like this [117]:

```
ncols          10
nrows          20
xllcenter      610158.757
yllcenter      126828.809
cellsize       2
NODATA_VALUE   -9999

785.045   784.766   784.487   784.24   784.12   784.0   ...   783.613
783.49    783.56    783.6     783.64   783.6    783.7   ...   783.6
...
```

To achieve implicit modelling using functions and communication with Grid Map[3], a secondary grid type as a regular raster is chosen as the preferred encoding for terrain throughout this research. In Figure 3.7, we see a regular grid DTM in a 2-meter resolution on the Gürbe River in Bern. Its data structure is

---

[3] Grid Map is a C++ library with ROS interface to manage two-dimensional grid maps with multiple data layers. It is designed for mobile robotic mapping to store data such as elevation, variance, colour, friction coefficient, foothold quality, surface normal, traversability, e.g.. It is used in the Robot-Centric Elevation Mapping package designed for rough terrain navigation [117] and used extensively on HEAP.

simple, well understood, and allows for the application of distance functions as described in the next paragraphs. The plugin Docofossor as described in Section 3.4 implements a similar data structure as the ESRI ASCII raster format, however it is optimised for Grasshopper in Rhino 3D (see 3.4.2).

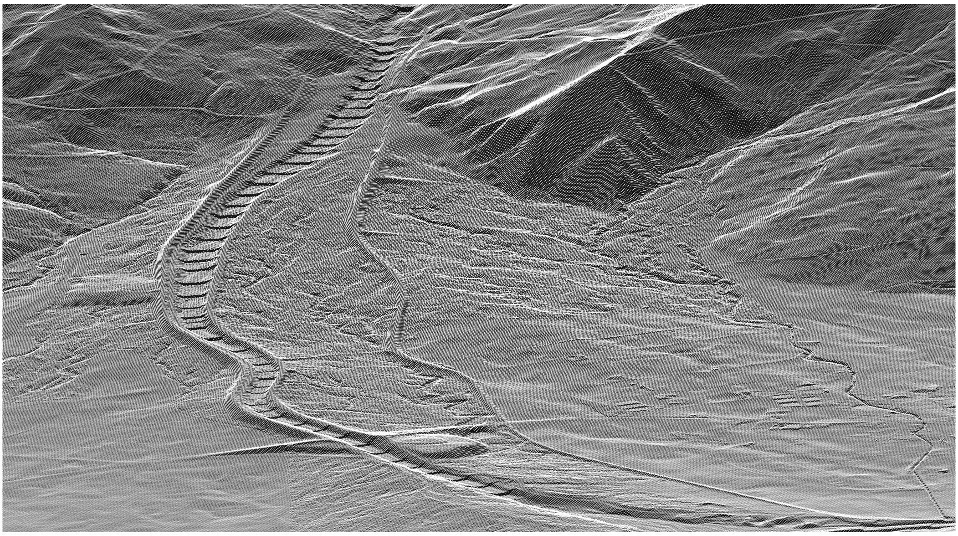


Figure 3.7: Illustration of a raster DTM, filtered to 1-meter resolution showing the bare terrain of the transitional zone of the Gürbe River in Canton Bern.

3.3 Terrain Modelling with Distance Functions

Because of the formal nature of terrain, an irregular or regular grid of points is the best way to describe it. Designing terrain in CAD software is an extremely tedious task because they mostly work with boundary representations (BRep), so the data has to be converted to either a polygon mesh or NURBS surface (see Section 2.3.2). Many Boolean operations on large meshes or NURBS are almost certainly doomed to fail [118]. To be able to respond to changing site conditions in a dynamic fabrication environment, topographic design adjustments have to be encoded parametrically. For this reason, this chapter outlines the application of function representations (FRep) to terrain data. This allows for many Boolean operations on a single data set. Furthermore, because the tools are written in Python, it can be used in the parametric modelling environment of Grasshopper or in COMPAS. The tool has been developed in collaboration with Mathias Bernard from Digital Building Technologies group at the ETH Zurich.

3.3.1 Digital Representation of Terrain

Point Representation

It is possible to use the points of a DTM or the raw point cloud as a representative format for landscape architecture. Point cloud editing tools are becoming more mainstream and result in a new view on the landscape [119]. However, the unstructured and large point cloud datasets are still challenging to work with as a terrain modelling tool [75]. The inverse is also true, the low density of points in a DTM is often not adequate for design representation, hence the widespread use of contour drawing or the rendering of a DTM as a mesh or NURBS surface. For performative aspects of the landscape, the DTM lends itself perfectly for interoperability with analysis or simulation tools that already exist in GIS applications.

Boundary Representation

We have seen that a DTM can exist as a rectangular grid or as a triangulated irregular network. Editing such networks in conventional CAD software requires this network to be translated into a mesh or NURBS surface in order to take advantage of the modelling and rendering tools [120]. Most CAD software describes geometry explicitly, e.g. in NURBS or meshes, where every point, curve or surface is defined by coordinates in space. The translation to a mesh is rather straightforward, because the points become the vertices of the mesh, for example using a Delauney triangulation. Translation to a NURBS surface, however, is difficult because of the complexity of terrain structures and resolution. There are generally two methods that change the existing network: destructive and non-destructive network operations. The non-destructive operations require vertex editing of the network: e.g. changing the position of a single vertex. Destructive network operations involve trimming or splitting in the case of a surface representation, or Boolean operations for constructive solid geometry.

Almost all modelling methods currently in use by landscape designers use destructive network editing in either polygon mesh or NURBS format. Both methods however handle large amounts Boolean operations poorly. Exceptions are ZBrush or Autodesk MudBox, that use pixols or voxels to represent 3D geometry. These programs are powerful in their digital sculpting capabilities, but lack the editing precision that vital for landscape construction purposes. Below is an explanation of vertex editing using non-destructive implicit modelling methods.

Function Representation

However, there exists a second method to describe geometry implicitly where shapes are defined as a definition of the entire space [121]. As Bernhard, Hansmeyer, and Dillenburger [82], mentions many names are used interchangeably like volumetric modelling, implicit modelling, or function representation as its name. With this method, every point within the space is the result of a function describing a shape. So instead of defining coordinates, every point now gets a value that describes its distance to the shape, and the surface lies where the function equates to 0. We call this the distance function. By creating a surface through all points with a value of 0, a shape can be rendered and made visible in the CAD software.

With this method, Boolean operations become manageable because we no longer have to find the intersection of surfaces or solids, but they can be calculated using simple arithmetics. Combining objects to each another can be calculated by solving the equation $min(a,b)$. Intersections can be found using $max(a,b)$ and subtraction follows $max(a,-b)$, $max(-a,b)$. See the work of Bernhard, Hansmeyer, and Dillenburger [82] for a full description. After these operations have been executed, a polygon mesh can be rendered in case this is necessary for design validation purposes. Bernhard describes how a simple rectangle in 2D coordinate space can be described explicitly by their vertex locations: $V(a/2,b/2)$, $V(a/2,-b/2)$, $4V(-a/2,-b/2)$, $V(-a/2,b/2)$ and by combining the vertices in a rectangle using $L(1,2)$, $L(2,3)$, $L(3,4)$, $L(4,1)$ (see also Figure 3.8). The vertex V consist of an x and y coordinate, and the line L gets coordinate pairs for start and endpoints. The implicit methods use the signed distance function (SDF) of a point (x,y). Here, the same rectangle can be defined as the following function $d = max(|x-a/2|,|y-b/2|)$. Any point in 2D space can now be evaluated, where positive values of d lie outside the rectangle, and negative values inside. Where d is positive, the point will lie exactly on the edge of the rectangle. The next section describes how this method is adapted to digital terrain models in a 2.5D application.

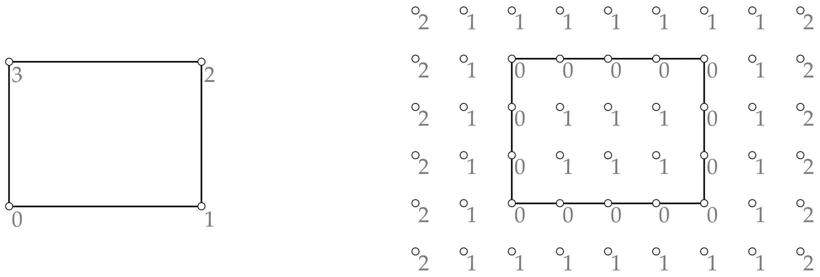


Figure 3.8: On the left a rectangle defined in explicit coordinate space by four points and lines connecting each point. On the right, the same rectangle defined as a signed distance function. The rectangle gets its dimension where the function $d = max(|x - a/2|, |y - b/2|)$ equals to zero. Interpreted from Bernhard [122].

3.3.2 Modelling using Distance Functions

The specificity of terrain data makes the translation of existing design tools made for industrial design or architectural design difficult. While there exist many tools to analyse large-scale terrain data in geographic information system (GIS) software, specific modelling tools geared towards landscape design hardly exist (see Section 2.3.2). This Section will explain how terrain data can be efficiently and intuitively modelled using new computational modelling methods based on distance functions.

Modelling Operations

Modelling strategies in terrain align conceptually and as data structure to points, lines and surfaces. In an attempt to move away from object-based thinking, Allen [123] introduced the idea of "field conditions". Instead of understanding architecture as objects on an empty canvas, he took an interest in the formative principles of local conditions within the larger field. Similar to this concept, modelling terrain is about the manipulation of a surface that is embedded in a virtually never-ending landscape; its condition is one of relations between points, lines and fields rather than discrete objects. Put simply, for digital terrain modelling, it makes sense to model with points or lines within a field of elevation data. Here, it is about the relationship these geometries have to terrain, which can be described by its distance to it. The input geometry can therefore simply be defined in CAD software as a point, a line (or b-splines), or region, while the underlying elevation map in the form of a regular grid is queried for its distance to this geometry. By applying algorithms (distance functions), one can now start to change the terrain map by free-form or parametric modelling. Sculpting digital terrain or moving earth using a machine can also be understood symbolically as the *movement* of a *shape* through a solid. Based on the work of Ervin and Westort [124], a similar approach is undertaken in this research where a primitive shape is applied to a motion in the form of a path (see Section 3.4.1). Before we list the primitive shapes and actions, the fundamentals are explained in the next paragraphs, which was partly published in Hurkxkens and Bernhard [118]. The library of shapes and motions are explained in the tool development of Docofossor, see Section 3.4.

Distance Field

Applying distance functions to a regular DTM requires the setup of the distance field first. Instead of having the distance function equate to 0 at the surface, the height values determine the distance to 0, e.g. sea level. Now the distance field becomes a simple height-map where the values are given by its elevation as displayed in Figure 3.9. The data structure for the distance field now consists of the definition of the grid and accompanying z values. By applying a distance function on every point in the grid using an iterator, Boolean operations can be calculated simply by shifting the point up or down, while keeping the network topology intact.

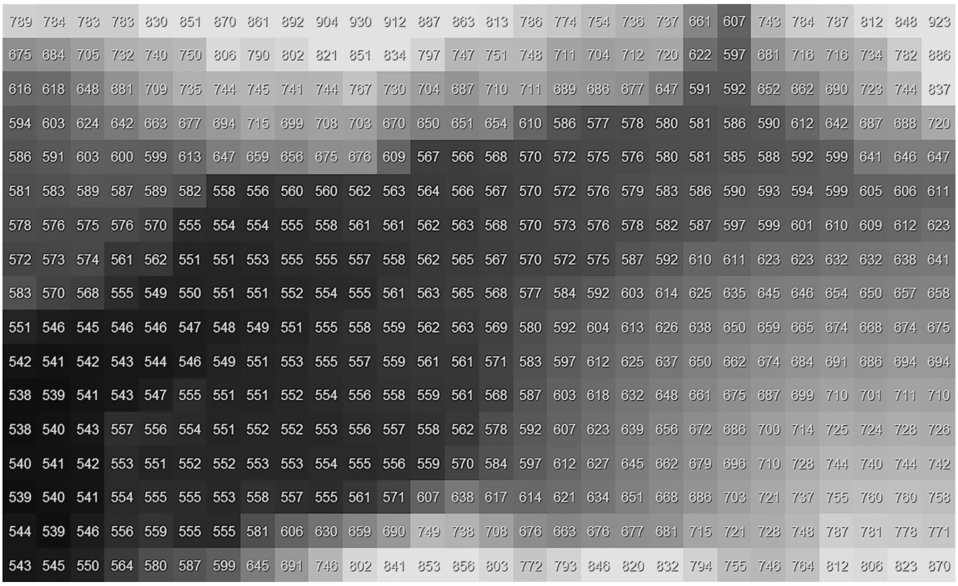
Absolute Functions

Absolute functions operate directly on the terrain using absolute coordinates, e.g., the distance functions depend on the z-coordinate location of the input geometry. In Figure 3.10 we look at a simple example where we make a fill on the terrain df at point p. The user inputs are p, w, h and the angle α.

Again, the distance function consists of two parts. Part one determines the height for the points that lie above df and within w. In this case, the height of the points is simply given by the z-coordinate of p:

$$\begin{aligned} & z1 = p.Z \qquad (3.1) \\ & \text{constraint by} \\ & z1 \geq df \quad \text{and} \quad dx \leq w/2 \end{aligned}$$

The second part determines the height for the points larger than df but



789	784	783	783	830	851	870	861	892	904	930	912	887	863	813	786	774	754	736	737	661	607	743	784	787	812	848	923
675	684	705	732	740	750	806	790	802	821	851	834	797	747	751	748	711	704	712	720	622	597	681	716	716	734	782	886
616	618	648	681	709	735	744	745	741	744	767	730	704	687	710	711	689	686	677	647	591	592	652	662	690	723	744	837
594	603	624	642	663	677	694	715	699	708	703	670	650	651	654	610	586	577	578	580	581	586	590	612	642	687	688	720
586	591	603	600	599	613	647	659	656	675	676	609	567	566	568	570	572	575	576	580	581	585	588	592	599	641	646	647
581	583	589	587	589	582	558	556	560	560	562	563	564	566	567	570	572	576	579	583	586	590	593	594	599	605	606	611
578	576	575	576	570	555	554	554	555	558	561	561	562	563	568	570	573	576	578	582	587	597	599	601	610	609	612	623
572	573	574	561	562	551	551	553	555	555	557	558	562	565	567	570	572	575	587	592	610	611	623	623	632	632	638	641
583	570	568	555	549	550	551	551	552	554	555	561	563	565	568	577	584	592	603	614	625	635	645	646	654	650	657	658
551	546	545	546	546	547	548	549	551	555	558	559	562	563	569	580	592	604	613	626	638	650	659	665	674	668	674	675
542	541	542	543	544	546	549	551	553	555	557	559	561	561	571	583	597	612	625	637	650	662	674	684	691	686	694	694
538	539	541	543	547	555	551	551	552	554	556	558	559	561	568	587	603	618	632	648	661	675	687	699	710	701	711	710
538	540	543	557	556	554	551	552	552	553	556	557	558	562	578	592	607	623	639	656	672	686	700	714	725	724	728	726
540	541	542	553	551	552	552	553	553	554	555	556	559	570	584	597	612	627	645	662	679	696	710	728	744	740	744	742
539	540	541	554	555	555	553	558	557	555	561	571	607	638	617	614	621	634	651	668	686	703	721	737	755	760	760	758
544	539	546	556	559	555	555	581	606	630	659	690	749	738	708	676	663	676	677	681	715	721	728	748	787	781	778	771
543	545	550	564	580	587	599	645	691	746	802	841	853	856	803	772	793	846	820	832	794	755	746	764	812	806	823	870

Figure 3.9: A raster grid of a valley landform displaying the cell values as the distance field from sea level, e.g. the height map.

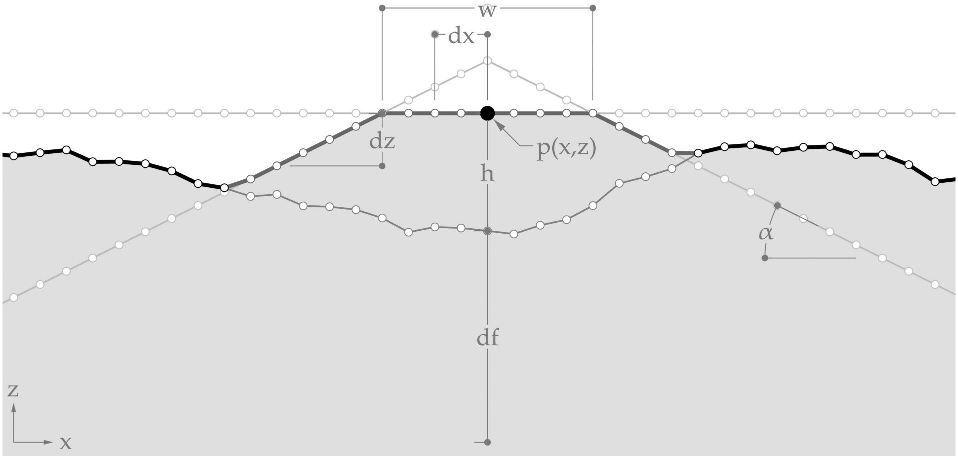


Figure 3.10: Section through a distance field where the point *p* is given in metric space (absolute). By applying a distance function from point *p* to each cell of the distance field, new values can be obtained.

outside w. Here, the distance function is given by:

$$z2 = p.Z - (|df.X - p.X| - w/2)tan(\alpha) \tag{3.2}$$

constrained by

$$z2 \geq d_f \quad \text{and} \quad d_x \geq w/2$$

Because all the calculations depend on the $p.Z$ coordinate and not on the $df.Z$ coordinate, we consider them absolute. Therefore, any input geometry has to be drawn in absolute coordinate space using real elevation values. The volume can be calculated using $p.Z - df.Z$ multiplied by the cell size area.

Relative Functions

Relative functions operate relative to the existing terrain, e.g., the distance calculations do not depend on the $z\text{-}coordinate$ location of the input geometry. Instead, the height is set as a parameter. In Figure 3.11 we look at a simple example where we make a fill on terrain df within an area p. The user inputs are p, h and the angle α.

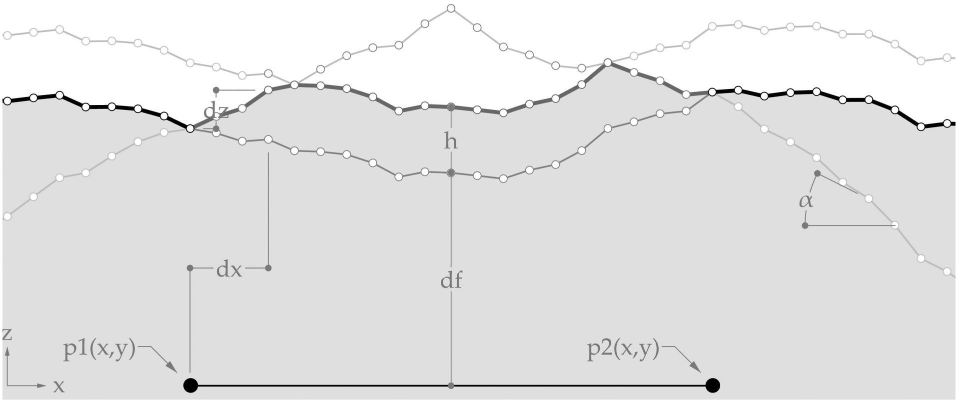


Figure 3.11: Section through a distance field. By applying a distance function from the closest point $p1$ or $p2$ to each cell of the distance field, new values can be obtained.

The distance function consists of two parts. Part one determines the slope connecting the filled volume back to the terrain. In this case, the distance function defines the new point location by finding the closest point p from $df.X$, and solving:

$$z1 = df + (|df.X - p.X|)tan(\alpha) \tag{3.3}$$

constrained by

$$z1 \geq df$$

The second part determines the height of the fill. In this case, the distance function is simple:

$$z2 = df + h \tag{3.4}$$

Finally, we can combine part one and part two by looking for all the values where the following constraint is true:

$$z2 \leq z1 \tag{3.5}$$

This results in all the points to be modified will lie inside area p and are larger than df, thus obtaining a new elevation value (there are multiple constraints that can lead to this result). Because the calculations all depend on the value of df, they are relative to the existing terrain and only needs 2D input in the form of a point, a path or an area. Fill volumes can now also be calculated by multiplying dz with the cell size area of the grid.

Generative Functions

Artificial topographies can be applied to a DTM the same way relative functions operate on it. A function that describes an algebraic surface can be used to generate the displacement. In the following example a simple sine function is used displace the z coordinates relative to the distance field, while incorporating a falloff towards the edges to blend it in the topography. Figure 3.12 shows how the user inputs of the wavelength (wl), the amplitude (a) and the blending distance (b) are applied to the distance field. The distance function for any point within p where dx is larger than b is given by:

$$z1 = df + sin(df.X * 2 * \pi/wl) * a \tag{3.6}$$

constraint by

$$z1 \geq p1.X + b \quad \text{and} \quad z1 \leq p2.X - b$$

For the points that will blend into the surface, a factor b is applied from 0 to 1:

$$f = dx/b \tag{3.7}$$

constraint by

$$dx \leq b$$

The displacement is thereby reduced to 0 when the artificial topography joins the original elevation. In this way, any generative distance function can be used to alter the distance field.

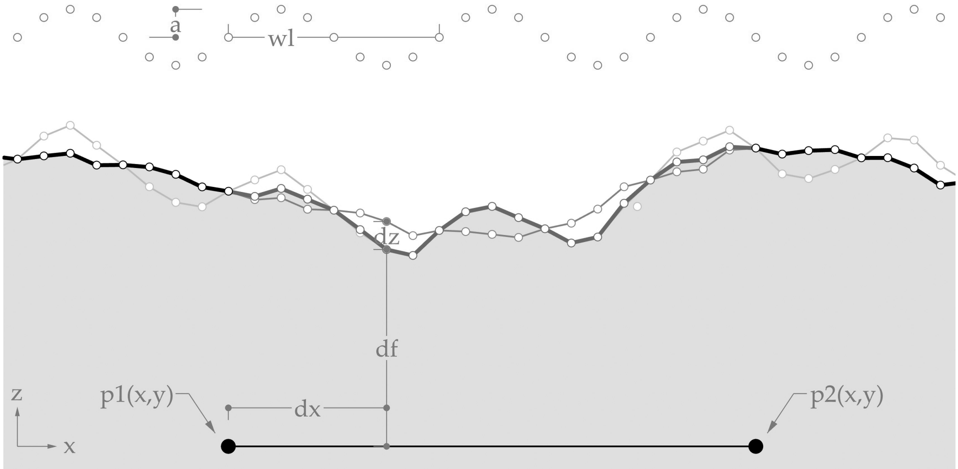


Figure 3.12: A 2D sine function applied to the distance field. The distance to points $p1$ and $p2$ define the extend and amplitude of the sine function.

Apart from the three examples given above, a component library in the visual programming interface Grasshopper 3D has been made to ease the modelling of terrain without the need for any coding. This was particularly important for the three experimental design studios described in Chapter 5. Here, it would not have been feasible to teach the students how to code distance functions within the timespan of a single semester. Following below is the description of the component library of the newly created digital terrain modelling plugin named Docofossor.

3.4 Developing Terrain Modelling Tools

The computational[4] terrain modelling tools discussed in this chapter have been made accessible as a Rhino Grasshopper plugin called *Docofossor* for the design research studios discussed in Chapter 4 and 5. This section shows an overview of the various components that were developed within the scope of this research.

3.4.1 Shapes in Motion

The easiest way to understand modelling terrain is its relation to the art of sculpting. Westort offers the following definition of sculpting as:

> *"The act of applying tools to materials via methods to enable the realization of three-dimensional forms. A sculpting method involves a feeling of expressive geometric control over a material from simultaneous, multiple degrees of freedom of movement resulting in a visible state change to the material." [32]*

As such, we can define terrain modelling by a shape (the tool) and a motion (the method). This relates directly to earth-moving with heavy equipment where the *shape* of the bucket *moves* through the terrain under machine control. It is tempting to define the shape as an excavator blade or bucket, or as a shape of common landforms. However, this would limit the possible formal space to precisely those geometric descriptions. Instead, the goal is to create a library of abstract primitives that enable the construction of any shape, whether they are parametrically, algorithmically or even computationally acquired. Therefore, the component library is focussed on primitive forms that in combination can create an increasingly complex geometry from primitives like a mount, a swale, a berm and a dike.

Similarly, the motion of a shape through a terrain should not be limited to the freedom of an excavator, but instead encompasses the full freedom that a digital environment offers. Here we can think of no motion at all (the point), motion along a path (the curve), and motion on an area (a closed curve). In all cases, the shape is applied to this explicit geometry as a cut or a fill, or a combination of both.

The differentiation of modelling tools as a graphic user interface has certain limitations, similarly to how pure coding can also be a daunting task for a de-

---

[4] As described in Section 2.3.2, the word computational modelling is used for design techniques that rely heavily on mathematics, physics, and computer science to study the behaviour of complex systems and their interaction through simulation. Using the word *computational* instead of *digital* or *algorithmic* for the proposed terrain modelling techniques is a bit of stretch as Docofossor relies on simple distance functions. However, this word is specifically chosen because Docofossor facilitates computational methods, and its future development is geared towards more computation as well.

signer. Instead, multiple techniques are combined to create an interface to terrain modelling that enables the power of computation, but allows for parameter control and free-form drawing as well. Because of these reasons, Rhino 3D has been chosen to implement free-form modelling of the motion (which includes a NURBS library for drawing the important s-curves in landscape design, see Section 2.2.1), while its graphical programming environment allows parametric control of the dimensional parameters of the shape. Finally, the distance functions are wrapped into easily accessible components within grasshopper to make the tools available without any scripting skills. A single operation starts with the selection of a relative or absolute operation (see Section 3.3.2), whether it should be a cut or a fill, if it should be applied to a point, a curve or an area, and what dimensions it should take (see Figure 3.13). As a workflow, multiple motion-shapes can be linked together to create a chain of modelling operations necessary to achieve the desired result.

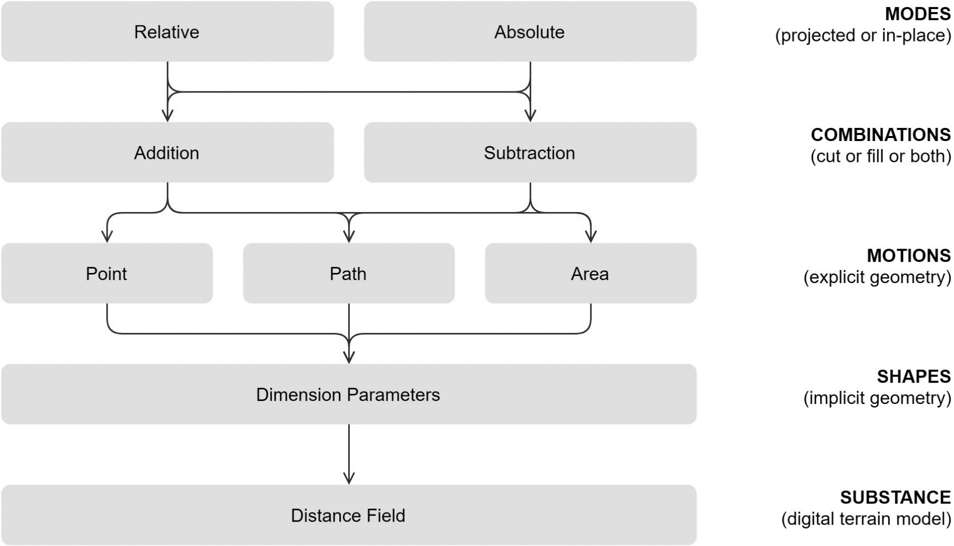


Figure 3.13: The conceptual levels and their naming scheme of the workflow in Docofossor. Through the selection of modes, combinations, motions, shapes and substance a new form is acquired through the modification of the distance field.

3.4.2 Component Library of Docofossor

The terrain modelling plugin is developed for Grasshopper, a visual programming environment in Rhino 3D and enables simple terrain modelling operations in cut and fill [118]. The application of the distance functions operate on points, paths (lines, polylines or curves), areas (closes polylines or closed curves) and also surfaces[5]. In all cases, however, the closest distance from grid points to the geometry has to be calculated, hence the name distance functions. In Docofossor this is done directly or using the build-in class methods from RhinoCommon or via the Rhinoscript python implementation. The components are made available through a toolbar as visible in Figure 3.14, separated in the categories analysis, generative, geometry, grid, I/O, absolute operations and relative operations. Following below is a high-level overview of the components in each category, and how they have been used in the research experiments.

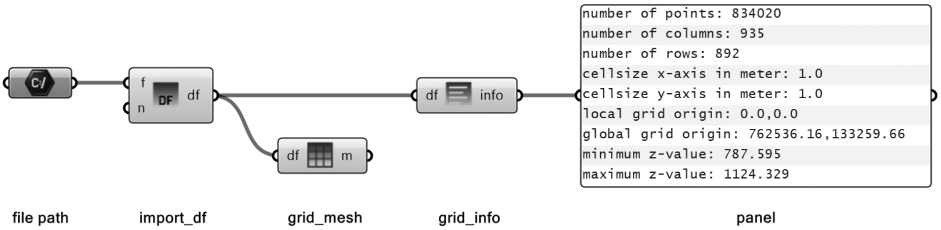
Figure 3.14: The toolbar of Docofossor within Grasshopper where the components are organised in seven categories; I/O., Analysis, Grid, Generative, Absolute Operations, Relative Operations, and Geometry.

Data Structure and Interoperability

The Docofossor list $df[]$ consist of a header part (dimensions) that defines the properties of the grid such as the cell size, the number of rows and columns, and the coordinates of the origin of the grid. The header information is followed by z-values coming from a DTM in column-major order starting bottom left. The advantage of separating the dimensions of the grid from the elevation data relates to smaller file sizes and the interoperability with Grid Map, developed at the RSL for mobile robotic navigation as used on HEAP (see Section 4.4). One of the main reasons for developing Docofossor is an easy interoperability between different software packages which is why the data structure is kept very similar to the ASCII format. This proved to be very convenient, as topographic changes due to mass movement simulations that are discussed in Chapter 5 were easy to add or subtract from the designed surface. The I/O category provides the input and output components for elevation data as text files in *.xyz or *.asc file format. An empty grid component, as well as the option to convert explicit rhino geometry into the Docofossor distance field, are provided as well. Each import component also enables to load a subset of the DTM by filtering out the rows and columns. This can be done at any time, making it possible to dynamically change the resolution of the grid while designing or visualizing the terrain model. Because all operations in Docofossor are done solely on the distance field, it is not represented automatically in the Rhino environment but exist only as data in memory. For this reason, both the Grid Points and Grid Mesh components translate the implicit distance field to explicit geometry ready for rendering in the viewport (Figure 3.16).

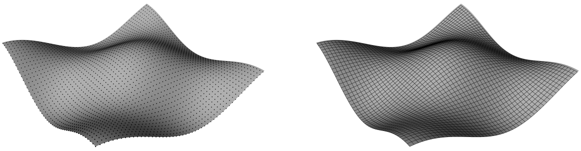
---

[5] The surface component was added as a backup, in case the shapes available in Docofossor would not achieve the desired result. The development of available primitives is still ongoing



```
number of points: 834020
number of columns: 935
number of rows: 892
cellsize x-axis in meter: 1.0
cellsize y-axis in meter: 1.0
local grid origin: 0.0,0.0
global grid origin: 762536.16,133259.66
minimum z-value: 787.595
maximum z-value: 1124.329
```

Figure 3.15: Data import example from Docofossor. The Grid-info component provides information from the dimension list, global and local coordinates, along with an indication of the elevation values, amount of points and resolution.

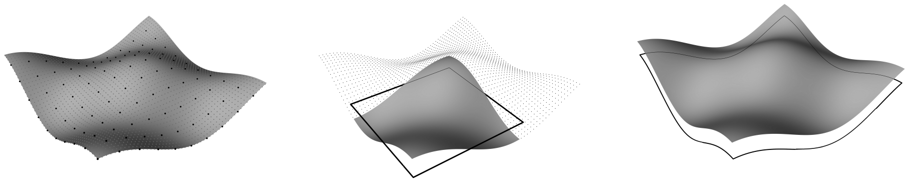


(a) Grid points (b) Grid mesh

Figure 3.16: Two components that translate the elevation data of Docofossor into explicit geometry to make it available for presentation in the Rhino 3D viewport.

Grid Translations

The Grid category tab provides tools that operate on the grid as a whole. After importing a DTM, the info component gives a quick overview of the all the dimensions of the data (see Figure 3.15). There two components that deal with localization, allowing a local custom origin that may vary from the global coordinate frame. Both values remain available at any time, which makes it easy to import other data sets and relate them as well to the local origin. At export time, the global origin is set, since neither explicit geometry nor the *.asc file format allows for two separate coordinate locations. The Region component makes it possible to display only a portion of the grid (Figure 3.17b). Together with the Filter component (Figure 3.17a), this decreases the computation time and mesh-visualization, which makes detailed adjustments work faster on a small portion of the terrain without having to compute the whole data set. It is also possible to increase the resolution of the grid at the moment a linear interpolation is made available. Finally, there are components that can shift the z-values up or down, add (Figure 3.17c) or subtract two separate grids from one another or get their difference-values. This proved to be very useful the application of mass movement simulation, as the erosion or deposition changes could be applied onto the terrain in Rhino.



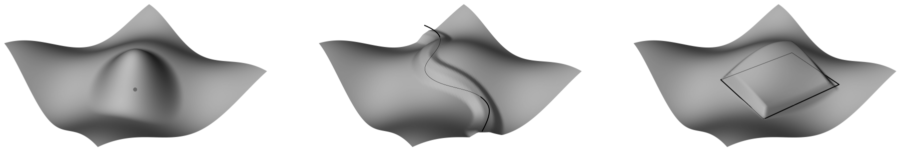
(a) Grid filter (b) Grid region (c) Grid addition

Figure 3.17: Three components from the Grid-category of Docofossor, allowing operations on the distance field as a whole: (a) lowering the resolution by subsampling, (b) selecting a region of the grid, and (c) the addition of two distance fields.

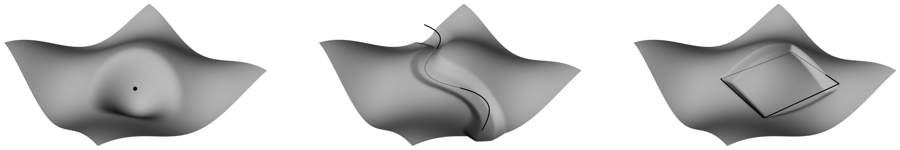
Cut and Fill Operations

The main reason for developing Docofossor was the ability to create tools for easy editing of cut and fill operations on a DTM. The implicit modelling methods allows free-form modification of terrain data without the need to encode it as explicit geometry. This makes multiple Boolean operations possible on large terrains which would have been virtually impossible using mesh or NURBS encoding as available in current CAD software (see Figure 3.21). The modelling tools provided by docofossor are divided in two categories: relative (Figure 3.18) and absolute (Figure 3.20), see for the explanation Section 3.3.2). Within each category, they have been grouped by addition (a fill) and subtraction (a cut) operations that modify the terrain by points, lines, areas, and surface. All the components work with a local subset of the DTM for speed optimization. The user parameters that can be set relate to the dimensions (width and height) and the slope (in relation to properties of the soil). On the curve components, one can also choose to have different parameters on the left or right side of the curve.

The tools for cut and fill were used as the primary modelling method during the Robotic Landscape II and III design studios. They were developed because of the insights during the first studio experiments where it became clear that it was necessary to have access to better digital terrain modelling tools capable of translating robotic earth-moving concepts in a three-dimensional form. One of the added benefits of a parametric modelling approach is the ability to quickly change the dimensions of a cut or fill in response to changing site conditions or a design's evolution over time. Here, one can iteratively increase the depth of cut, the height of a fill or the angle of slope. Figure 3.19a and 3.19b show the grasshopper environment and a complete workflow from the import, the cut and fill operation, to the visualization and analysis of the terrain. As visible in the picture, the volume balance is tracked per individual component, but can also be calculated after many operations by comparing two df grids together, which also displays the separate cut and fill cubature. Whenever the design curve sits



(a) Fill on point (b) Fill on path (c) Fill on area



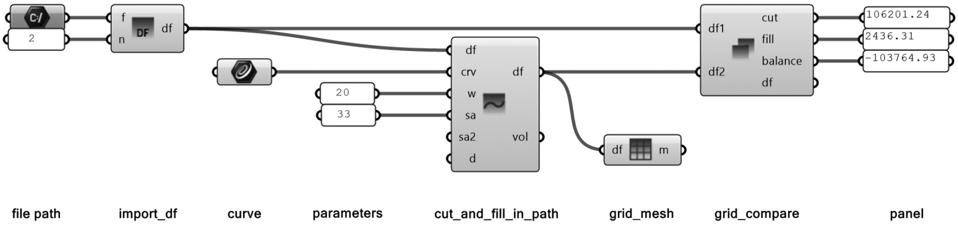
(d) Cut on point (e) Cut on path (f) Cut on Area

Figure 3.18: Relative cut and fill operations in Docofossor, operating on points, curves or closed curves respectively.

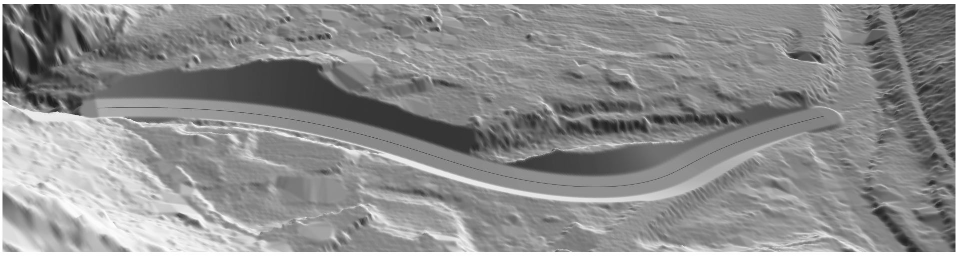
below the surface, a cut is made, and a fill operation whenever it hoovers over the surface. The linked topological connections, where the cut or fill meets with the original topography and how much volume is necessary to carry out the modification, is done automatically. This saves a considerable amount of time compared to modelling with boundary surfaces. It opens up the potential of evolutionary modelling and animation over time, concepts that are closely linked to robotic fabrication. Figure 3.22 also shows how this is applied to a surface, where the terrain model will take the elevation-values of the surface and establishes the fill or cut at a user-defined slope angle back to the original terrain.

Generative Components

The Generative components in Docofossor are a special case, as they operate as a *field* by relative modification. Here, there is no method or movement along a path, instead the modification of the terrain is handled solely through arithmetics. There are two components available: Noise (Figure 3.23a) Sine Wave (Figure 3.23b). Because newly created shapes have a very crisp and ideal appearance, the noise component makes it easy to apply roughness and randomness to such a surface. The Sine Wave component creates a perfect waveform, but because it is applied *relatively*, it can be useful to create local differentiation as well. In both cases, a fall-off towards the edges can be set, which creates a blend to the existing topography.

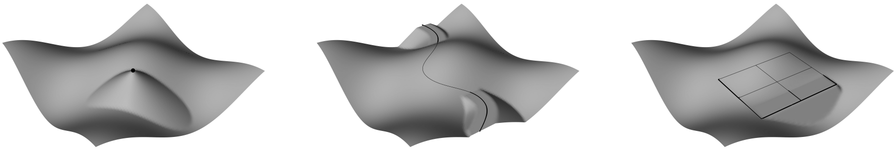


(a) The Import DF loads the elevation data and subsamples it by a factor of 2 for quicker load times. A curve determines the absolute position of the cut-and-fill-in-path operation with parameters for the width (20 meters) and slope (33 degrees). Finally, the distance field is rendered as a mesh and cubature of the cut, fill and total balance are calculated and presented in a panel.

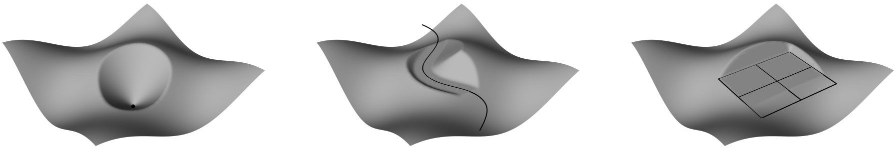


(b) The resulting presentation of the path-curve and the quad-mesh in Rhino with custom hill shading applied.

Figure 3.19: Examples of the Docofossor plugin in the Grasshopper environment as a cut-and-fill-in-path operation on an existing topography (a) and visualized in Rhino 3D (b).



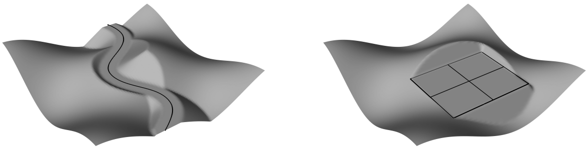
(a) Fill in point (b) Fill in path (c) Fill in surface



(d) Cut in point (e) Cut in path (f) Cut in surface

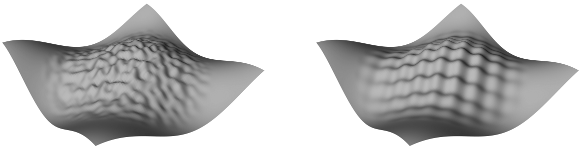
Figure 3.20: Absolute cut and fill operations in Docofossor, operating on points, curves or closed curves respectively.

Figure 3.21: Digital terrain model from Docofossor using many subtraction and addition operations on a single distance field. By students Roma Guldimann and Jonas Haldemann.



(a) Cut and fill in path (b) Cut and fill in surface

Figure 3.22: Combined cut *and* fill operations in Docofossor operating on a curve and a surface.

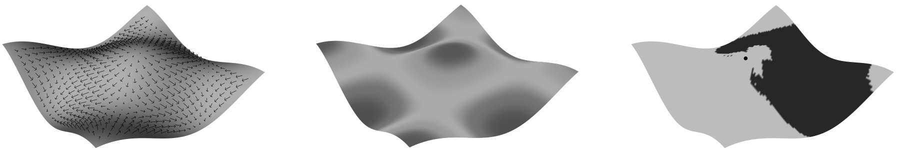


(a) Perlin noise (b) Sine waveform

Figure 3.23: Generative components in Docofossor operating on the distance field within a specified region providing parameters for amplitude, wave-length, and fall-off.

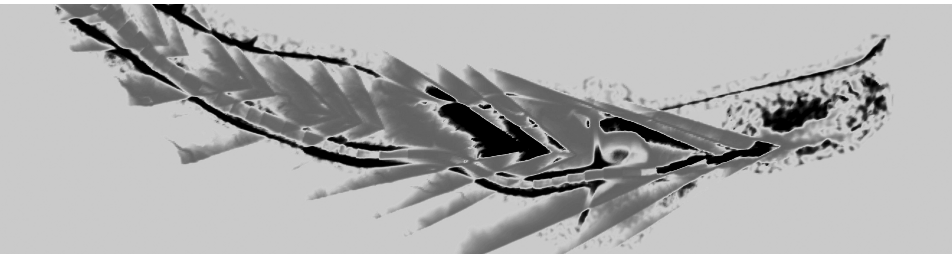
Analysis and Simulation

The analysis tools in Docofossor provide a set of landscape properties that can be used for a dynamic modelling and fabrication approach. The Grid Compare component displays the cubature in cut, fill and balance, and provides a difference map where the change of elevation between individual operations can be tracked. Of course, this is true for modelling operations but also during fabrication, as explained in Chapter 4. The next set of analysis tools provide slope and orientation of the individual cells, as well as representation tools to colour a mesh based on this analysis. Two more advanced components can calculate the shortest path and a viewshed from the DTM (see Figures 3.24a and 3.24b). One final feature is the ability to communicate with numerical analysis tools for natural processes and import the results back onto the distance field in Docofossor. There exist many computational tools relating to the earth sciences that rarely make it to the design phase of the project. Especially hydrological and mass movement simulations can be vital for an informed design method. While the computation itself is done in an external software package, Docofossor tries to facilitate the interoperability between the modelling tools and the simulation tools, providing access to scientific validation methods as well as a truly iterative design process.

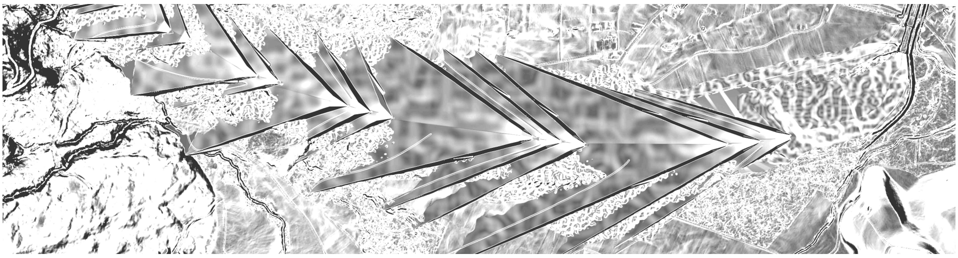


(a) Slope vector and orientation (b) Height gradient (c) Viewshed analysis

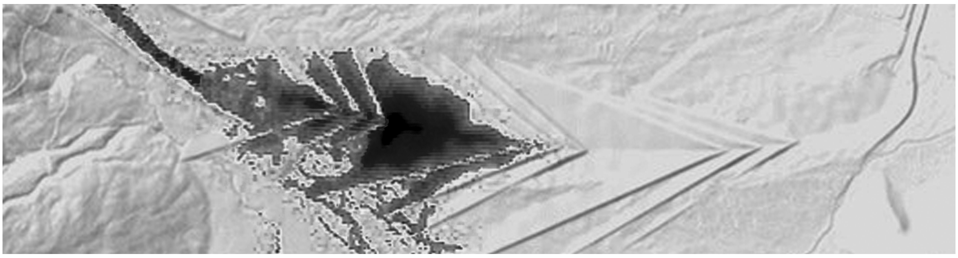
Figure 3.24: Three analysis components in Docofossor that give access to landform classification as well as more advanced algorithms.



(a) Cut and fill analysis



(b) Slope analysis



(c) Mass movement simulation using the RAMMS software tools

Figure 3.25: Examples from the design experiments described in Chapter 5 using features from Docofossor to analyse cut and fill, obtain slope aspect, and import simulation results. By students Mathias Häcki and Matteo Zwyssig.

3.5 Summary

The development of Docofossor enables both parametric and computational methods in the application of digital fabrication and large-scale landscape design. The new aerial lidar system provides the necessary elevation data to establish the design and the robotic feedback loop between sensing, modelling and manipulation. This has been implemented to various degrees of automation throughout this dissertation. As we have seen in Section 3.2.2, a DTM contains either structured or unstructured points. Even though there exist many different techniques for point acquisition (like radar, lidar or photogrammetric surveys), the output of this data to a DTM results in a rather uniform format that is widely used. These DTM's are encoded using a 2.5D regular raster grids, and a layered approach can overcome most drawbacks that a full three-dimensional distance field would provide, while maintaining interoperability with existing simulation packages. Grid Map, the mapping implementation for HEAP, also allows the storage of multiple layers that can hold this information, which also enables various state-goals in terrain (see Section 4.4).

The duality between implicit and explicit modelling methods was conceptualised by Bernhard [122] as full versus empty space. Where vector data and boundary representations construct new objects in empty space, raster data and function representations modify fields in an existing (full) space. Because a landscape project never starts from a blank canvas, the application of implicit methods is a good fit. By combining implicit methods with free-from modelling tools, both intuitive and precise landscape structures can be achieved with Docofossor. As such, applying distance functions to terrain data makes it easy to embed new designs into existing sites. It also detaches the underlying topological network from the operations made in the topography, enabling dynamic updating of the DTM, which becomes essential when working with robotic construction processes within largely unknown environments.

The integration of models of information, design and fabrication also enables the application of simulation in natural granular material, where sedimentation and deposition processes can be computed using external software solutions which in turn is easily added to—or subtracted of—Docofossor's elevation data. The potential of generative components lies especially in their capability of responding to an analysis of existing landform. But more work needs to be done to make this a genuinely dynamic modelling approach as most design processes still leaned heavily on manual input (see 6.4). In this research, a responsive modelling approach has mostly been implemented in small scale physical experiments using a robotic arm, which is described in Chapter 4. However, Docofossor's modelling tools form the fundamental design technique for both the large-scale design experiments (see Chapter 5), as well as the full-scale robotic embankment prototype (see Section 4.4).

The development of Docofossor was encouraged by recognising that a fabrication approach using robotic technology could greatly benefit from digital modelling tools using parametric inputs and computational capability. Due to the lack of dynamic terrain modelling software today, a schism exists between models of information (as a geographic information system) and models of design (as intuitive and free-form methods). Designers had to choose between free-form modelling, parametric modelling and computational methods depending on their skill levels and the project. For this research, a focus on visual programming seemed to be to most valuable approach as it enables both free-form and programmatic inputs. This allowed the design experiments to be carried out with students without any prior scripting knowledge. However, it may be clear that GUI's are not everything [32], and that a digital-native approach using object-oriented programming with primitives and actions will become a necessity for future developments in this area.

Chapter 4

Substance and Grammar: Robotic Formation in Terrain

> *"I'm standing in the sand, surrounded by sand. I'm kicking into the sand; I keep digging. I'm digging myself into the sand, the sand mounds up in front of me as I dig further and further into the sand..."*
>
> —Vito Acconci [125]

4.1 Overview

Working with robotic systems in a loose and granular substance requires sensing and control systems to cope with the chaotic character of the material at hand. This inherent difficulty of autonomous earth-moving has left landscape architecture mostly unaffected by on-site robotic fabrication technologies today. While this NCCR research project for robotic landscaping is certainly not the only attempt to model terrain autonomously, for the first time, it combines a design discipline to the engineering development. While the Robotic Systems Lab of prof. Marco Hutter worked on planning and control systems for the shaping of free-form trenches and embankments using an autonomous walking excavator [126], this dissertation conducted design experiments to explore this new construction method for its potential in terrain. These experiments with granular material and robotic processes were explored within the framework of design research studios in a collaboration between the Chair of Landscape Architecture, Professor Christophe Girot and Gramazio Kohler Research (see also Chapter 5). At the end of this Chapter a real world prototype is presented that developed tools and processes towards the integration of design and fabrication environments in collaboration with the Robotic Systems Lab.

This Chapter starts with outlining robotic controls mechanisms using cybernetic theory and gives an account of a procedural, topological, and topographic approaches. This is followed by defining the first two core concepts of dynamic formation in terrain: substance and grammar (Chapter 5 outlines the other two core concepts; process and form). The constraints description of the material system (sand, gravel, rocks) and fabrication grammar (a set of dynamic rules directing the motion of a tool through a substance) evolved throughout the experiments in robotic formation. The design experiments were conceived to look specifically at three different operation cycles in the manipulation of terrain: 1. spreading and compression cycle, 2. dumping cycle, and 3. combined digging and dumping cycle. As such, they mimic the capabilities of HEAP in a model-scale sandbox using a robotic arm. Since the design techniques for robotic instruction has mostly been developed by the team of Gramazio Kohler Research, it is briefly outlined in Section 4.3. Instead, through a dynamic process between robotic earth-moving and analysis techniques, specific design strategies for working with terrain are defined. These strategies and concepts are then extrapolated in Chapter 5 for large-scale landscape design and fabrication processes. In Section 4.4 a complete robotic feedback loop is established using Docofossor among other tools that were developed within the scope of this research. Parts of this Chapter has been published in the proceedings of the Design Modelling Symposium Berlin 2019, see Hurkxkens et al. [127].

4.2 Formation Processes in Granular Material

4.2.1 Levels of Constraint in Automation

First- and Second-Order Cybernetics

In Section 2.3.3 we have seen how robotic construction has evolved from mechanisation and automation by enabling bespoke fabrication while keeping all the advantages of automation. Through methods of material and machine computation, dynamic construction processes can be achieved. However, by responding dynamically to a natural system, a certain form of guidance needs to be implemented to direct its operation towards better performance instead of pure entropy. Cybernetic theory offers a distinction between first- and second-order control systems [128, pp. 207–212]. In a first-order system, the actual interim state is compared to the desired state, and the difference is computed. From here, adjustments can be made in order to steer the process towards the predefined final goal. In a second-order system, the actual state is compared to the desired state, but here the original final goal is evaluated as well. When there is an opportunity to adjust the final goal for better performance, a new goal can be defined. Now, which goals to set becomes the main question for the designer. This goal can be set on a purely formal level, as a performance, or as both. This can have big influences. To give an example, when a natural system performs very well on a certain ecological level, it is still possible that it would not be an acceptable outcome on a functional level for society. As such, the constraints of a system will eventually determine the possible space in which it can operate.

Procedural, Topological, and Topographic Approaches

It is important to delineate the gradient between procedural, topological, and topographic approaches to robotic earth-moving. Their difference originates from the survey; whether a found geometry or a designed geometry determines the movement of the tool through terrain. The topological approach is defined in assuming a structure, nodes, or formal relations that have to be achieved. Through iteration, the excavation and deposition cycles come closer and closer to the designed topology until it is within a certain range limit. The dynamic aspect comes from the operation cycles based on force, or using a feedback loop with 3D scanners in the design environment, where dimensional parameters like slope and available volume can be updated dynamically. In the procedural case, the approach relies solely on a rule-based grammar that is achieved without a predesigned form. Instead, any movement of the tool relates directly to rules that respond to the analysis parameters of the found geometry in terrain. We can call this outcome *emergent* since the forms appear almost magically from the interaction between the machine and the material. This type of system is more difficult to control, but can be understood and directed by iterative testing and adjustment of the rules. As such, it can continue forever and is open-ended. This trial and error approach relates more to form searching and moves beyond the "scan-and-design" approach as Carpo puts it [129]. This type of control operates in similar ways as a natural system, where form is dominated by internal laws of physics. The third approach is defined as topographic, where a complete shape description exists as a digital terrain model. Here, a designed topography is interpreted by the planning and control systems in a fabrication environment to achieve planning and control. This approach has not been tested in the small-scale formation experiments, but is explored in the full-scale robotic embankment prototype with HEAP. Combinations of these approaches is likely in most cases. The combination of a procedural and topological approach is explored in the formation experiments, where the topology is described dynamically, without having to define an exact position or surface. The topographic approach also makes heavy use of procedures, but they are not based on a found geometry but instead follow the form of the design. These approaches offer a separation of hierarchy based on scale. Where individual digging cycles can profit from a rule-based approach as demonstrated by Jud et al. [126], at the larger scale of the territory, different questions come into play that relate in a more obvious ways to topology and topography.

4.2.2 The Robotic Mechanism

The robotic mechanism enables dynamic construction. While concepts that incorporate feedback is nothing new [71], it is usually explored on the level of automation. Instead, this Chapter tries to uncover the architectural potential of a dynamic fabrication approach in terrain, where the existing form of the terrain starts to influence and determine the robotic operations that act in it (see also Section 2.3.3). Through sensor technology, the robotic operations respond to a particular terrain form, alters it accordingly, which in turn creates a new form and a new starting point for the next iteration. This *reflexive* process leads to a new design paradigm [110], where natural processes and human-made processes merge into a new *digital materiality* [104].

The feedback loop between the manipulation of the material, the resulting shape and the design environment is essential in on-site and mobile robotic fabrication. This also counts for working in terrain. The interaction of a bucket in soil, the collapse of trenches during excavation or the dumping of soil on a heap does not result in a precise and predictable geometry relating 1:1 to the actuator movement. Instead, after every operation, the current elevation map has to be updated in order to decide on the next move. A feedback loop has been established to fulfil this requirement between the sensing of terrain (survey), the modelling environment (design) and the manipulation of terrain (fabrication). Figure 4.1 shows the physical and digital flow of information in this feedback loop. Followed below is a discussion of each element in the robotic mechanism.

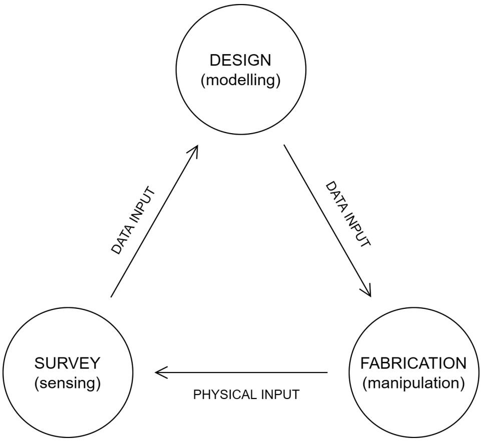


Figure 4.1: Feedback loop of the robotic mechanism showing the flow of data between sensing and modelling, and modelling and manipulation, while the physical material system forms the connection between manipulation and sensing.

Survey

The survey plays a central role in landscape architecture in general, and in earth-moving in particular. As we have seen, most autonomous earth-moving systems that exist today rely heavily on localization and mapping techniques (see Section 2.3 and 3.2). While institutional surveys, like those provided by national geographic survey bodies, only have to scan the terrain once, robotic systems rely on a continuous capture of the terrain to understand how it changes during excavation or deposition [126]. This is necessary because it is virtually impossible to predict the interaction of granular material in motion accurately. This also means that multiple DTM's have to exist at the same time. One map stores the original elevation of the terrain before execution, one stores the current elevation and is continuously updated, and one stores the desired elevation of the design. The difference map between the existing and current elevation informs how much cubature has been excavated, while the difference map of the current and desired elevation gives control over how much is left to excavate. Using real-time mapping techniques, one can inform where and how the next digging cycle will take place. Along with elevation, additional parameters can be acquired using force-feedback, ground-penetrating radar or multi-spectral imaging and can play a role in the design cycle as well.

Design

While the design objectives are set during the preparation phase, real-time modelling during execution enables dynamic fabrication strategies to take place. Using the current elevation map, it constantly validates the resulting form after every digging cycle. At a larger scale, it controls the overall form, dynamically adjust the shape according to available cubature and material properties, and can respond to unforeseen events due to ongoing natural processes on site. All these parameters should be updated dynamically in the design model and checked against material, progressive, fabrication, and topological constraints (see also Chapter 6). In this way, a robotic process can accommodate unforeseen conditions in natural environments.

Fabrication

Fabrication concerns the actual actuation of the robotic platform and manipulating of the material. Here, hardware determines the possible movements on-site, the movements of the robotic arm and the interaction between the end-effector (shovel, blade, gripper) and the material. All hardware components influence the way material can be manipulated, and thus determines the possible outcomes and design space. In Section 4.2.4, general rules for earth moment are discussed in more detail.

4.2.3 Substance: Natural Granular Material

Leveraging material computation (the physical interaction of natural particles) in granular material is an efficient and expressive method in the shaping of terrain. When exposed to external forces, the natural arrangement of particles always takes a final shape that is possible and follows logically from the forces applied to it. The space in which granular material operates and performs are defined by the material constraints. This thesis deliberately limits its medium to natural granular material like clay, silt, sand and gravel. This choice relates both to the digital tools as to the way the earth is moved using heavy equipment. The behaviour of natural granular material from small clay particles up to gravel are generalized and considered homogeneous in its digital representation and equipment use. Figure 4.2 shows the basic principles for identification of soils as defined by ISO 14688-1:2017 [130]. Here particle size defines common denominators like clay ($0 < 0.002mm$), silt ($0.002 - 0.06mm$) and sand ($0.06 - 2mm$). See also Figure 2.10 for the complete overview of texture classes. Up to and including cobbles, we can argue that digital tools do not have to treat every particle individually, and an end-effector can transform it as a single substance. Within these grain sizes, material manipulation can be done using a standard bucket or a grading bucket.

However, boulders would have to be treated as discrete objects and handled using a gripper of sorts [131]. For clarity, this thesis is oriented towards soil movements using a grading or excavation bucket. Therefore, the material- and fabrication constraints are for natural granular material up to 200 mm in diameter.

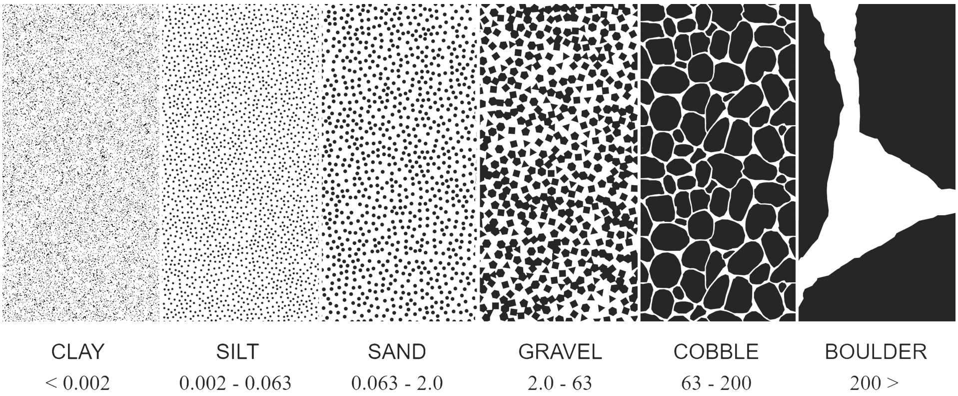


Figure 4.2: The 6 general categories of grain sizes by diameter in millimetre as defined by the ISO standard 14688-1-2017. Grain sizes taken into account for this thesis range up to and including cobbles.

The stability of sloped terrain is constrained by parameters such as mass, soil type and groundwater which together determine its mechanical behaviour. Analysis methods of slope stability can be done using limit equilibrium, finite element or numerical analysis methods. However, a large part of the mathematics involved in soil engineering can be eliminated using basic practices and principles of grading [132, p. ix]. While shear strength, lateral pressure, bearing capacity, and permeability are critical mechanical properties for the construction of functioning earthworks, it goes beyond the reach of this thesis. Instead, general rules are distilled and encoded to inform the design space using topological constraints.

Angle of repose and soil texture

The angle of repose in granular material determines the steepest slope achievable relative to the horizontal plane. Increasing this angle even further would cause the material to slump down. The angle of repose greatly differs depending on the soil texture, e.g. the found mixture of clay, silt and sand. It is difficult to classify the soil texture using remote instruments, and is usually done in a lab. Because of the soil horizon and spatially varying soil textures, the repose angle will not always be the same for a certain excavation area. It is therefore virtually impossible to predict the repose angle before earth movements have been made. However, interaction forces from a force-sensitive grading bucket in combination with dump tests can approximate the repose angle [133]. This also implies that the modelling freedom in the topography can only be accurately determined during construction. Current practices however rarely calculate the actual repose angle and work from past experience or rules of thumb. Here, a 2:3 slope (0° - 33.7°) is considered stable and is used in most road embankments [96]. Any repose angle higher than 33.7° requires soil stabilization methods using bioengineering, geotextiles, reinforced earth or retaining walls. It may be clear that earth-moving projects can benefit from an optimized soil texture map and subsequent cut and fill operations. This would increase the design space, enable a more efficient material culture and allow earthworks to express its local specificity. More concretely, the OSHA publishes a manual where the repose angle is related to its soil type. Figure 4.3 shows an overview that can be used in Docofossor while modelling or validating the topography.

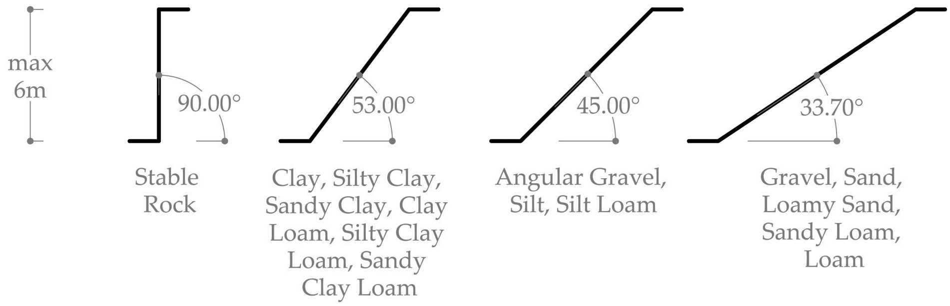


Figure 4.3: Guidelines for the maximum allowable slopes in the excavation of terrain based on soil texture, from the *OSHA Technical Manual Section V: Chapter 2 - Excavations: Hazard Recognition in Trenching and Shoring* [70].

Volume and soil consolidation

Soil consolidation and compaction is an essential aspect in earthworks due to the change in mechanical properties by decreasing its volume and allowing water to seep out. It is achieved by putting pressure on the soil mechanically or by gravity over time. The increase in volume from excavated material is difficult to predict but can be approximated using representative factors [37]. When the soil class is known, swell and shrinkage can be calculated (see Figure 4.4). However, it stays difficult to determine exact changes in volume and often material has to be added or removed from the site by trial and error. This can pose economical and also ecological challenges. An ongoing volume estimation should thereby be integrated within the desired construction plan do be able to adapt to changes in available material locally. This can be done with continuous 3D observation using on-machine or aerial surveying techniques (see also Section 3.2). Shrinkage and swell factors can then be calculated irrespective of the weight of the material. Docofossor can keep track of the cut and fill volume using a difference-map and expected cubature could be extrapolated forward from here.

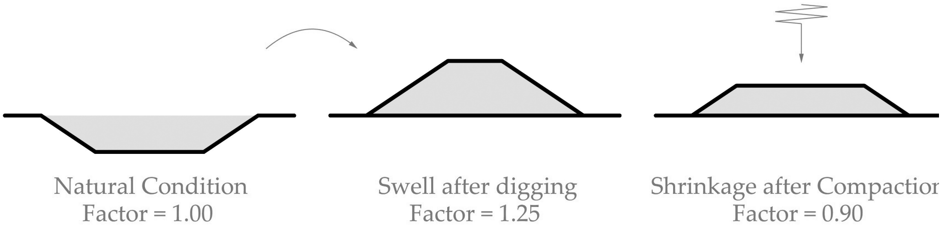


Figure 4.4: Example of shrinkage and swell factors in earth-moving based on the most common topsoil types. Factors taken from Schmitt et al. [37].

Soil Profile and Horizons

The soil horizon defines the vertical differentiation of material in terrain. Starting form the top, topsoil consist of large amounts of organic and matter, which decreases in the subsoil, and is virtually absent in substrate and bedrock. The topsoil is generally between 5 and 40 cm thick, and subsoil extends to depths of 50 and 150 cm [96, p. 110]. Topsoil is an extremely limited resource on earth and is rapidly depleting (see Montgomery [62] and Section 2.2.3). In any earthwork project, this has to be treated with care. It is often stripped and stored to be re-applied over the final topography after the terrain modelling has been finished. A specific soil profile can be encoded using a multi-layer approach in Docofossor

Unforeseen soil profiles or large boulders have a significant influence on the execution of a design. It might not be economically or ecologically beneficial to excavate or blast bedrock, or disturb the subsoil. Recent advances in ground penetrating radar show potential in encoding substrate and groundwater levels [134]. However, surprises will most certainly always arise during excavation, and regular updates to the soil profile layer may be necessary. The movement of the topsoil, subsoil and substrate trough a site during construction play a vital role in the ecological and landscape topological outcome of a project. The fabrication constraints determine to large extend the possible material movement apart from natural processes on-site, as is described in the next paragraph.

4.2.4 Grammar: Shapes in Motion

This dissertation defines the movement of a tool through a material as the grammar of robotic earth-moving. A set of rules are dynamically created by sensing various properties of the terrain. As such, a form is the result of the *motion* of the *shape* trough the *substance*. Here, the motion is constrained by the robotic platform, the shape is defined by the tool (excavator bucket), and the substance is the natural granular material of terrain. This procedure is not unlike how *shape grammar* operates. Initially introduced by Stiny and Gips [135], shape grammar is a set of shape rules that when applied recursively, generate a new form (see Figure 4.5). As an example, its technique has been applied to generate the plans of Moghul gardens parametrically, by computing with shapes that ultimately determine the channel and pathway layout [136]. Knight and Stiny [137] take this concept one step further, by computing with things (*making grammars*) rather than shapes, which necessitates a sensing action to interpret the result of the previous step. Similar to how the concept of *shape grammars* and *making grammars* establishes form by computing with shapes or things, earth-moving grammars describe the rules by which terrain-form is created. This is a dynamic process, where the movements are determined by the found material properties of terrain. As such, this can fundamentally only happen on-site and at the moment of production. Trying to preconceive all the variables that influence its final form is virtually impossible. Instead, the act of design does not only lie in the description of form, but involves the description of rules; the grammar of earth-moving. However, we should not forget that the ultimate object of design is form [19, p. 15] and that form is the starting point and outcome of any dynamic process (as described in Chapter 5).

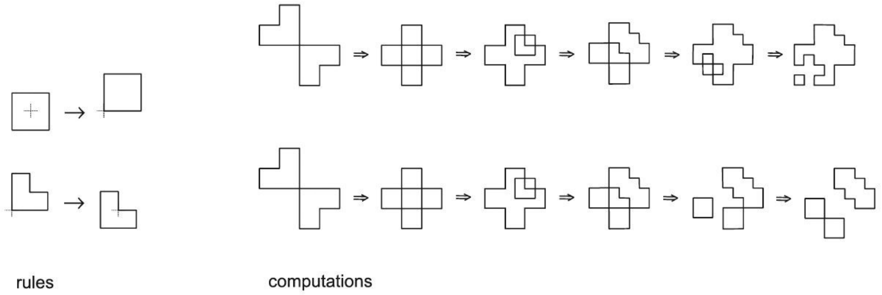
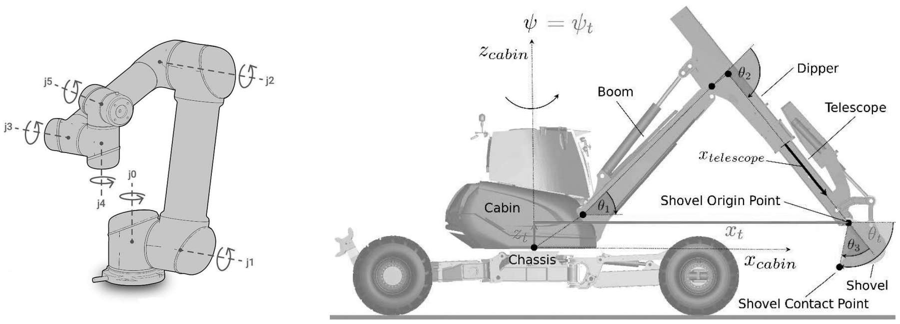


Figure 4.5: Illustration of a shape grammar with rules and two possible shape computations. Shape grammars compute directly with shapes in two or three dimensions, rather than with symbols, words or numbers. From Knight and Stiny [137].

Tool Motion

Mechanisation in construction has long been oriented towards systematisation, standardisation and prefabrication [138]. Through the application of computer-aided design, a separation between design and construction is challenged by reprogrammable tools [139]. This enables a custom design and fabrication processes while keeping the benefits of automation. In terrain, the potential of reprogrammable tools creates the possibility of a responsive design and construction processes; shaping is no longer bound to a predefined motion but instead can be dynamically updated during construction. This opens up two central potentials: firstly, it provides construction processes that respond dynamically to on-site conditions. Secondly, it enables construction processes that respond dynamically to evolving construction processes. This is particularly important for loose and granular material, as its behaviour is difficult to estimate in advance.



(a) The task space of a UR10

(b) The task space of HEAP

Figure 4.6: The task spaces of a Universal Robot UR10 and of the hydraulic excavator for autonomous an purpose HEAP, (a) from *Robotic Fabrication for COMPAS* [140] and (b) from Jud et al. [12].

In shaping terrain, all that matters is the handling of the tool. The machine that is attached to it is only there to support its application. While early robotic construction was constrained to the factory, autonomous construction is slowly but surely moving away from prefabrication towards the construction site itself [95]. This opens up a whole new category of possible tool movements and scale of production. Robotic fabrication is no longer limited to the range of a robotic arm but has become mobile and even aerial in scope [71]. It is this shift that has enabled robotic construction for landscape architecture.

The movement constraints of a robotic platform are determined by the way a tool can be positioned in space. This is defined by the workspace of the machine, where each individual joint has its own limited freedom of movement (see Figure 4.6). In the experiments, this was not a real constraint, as the scale of the robotic arm allowed for most motions of the tool in the sandbox. For the experiments with HEAP, the movement was largely predefined by the designed geometry and did not extend beyond the reach of the excavator.

There are a number of operation cycles that can be differentiated in moving

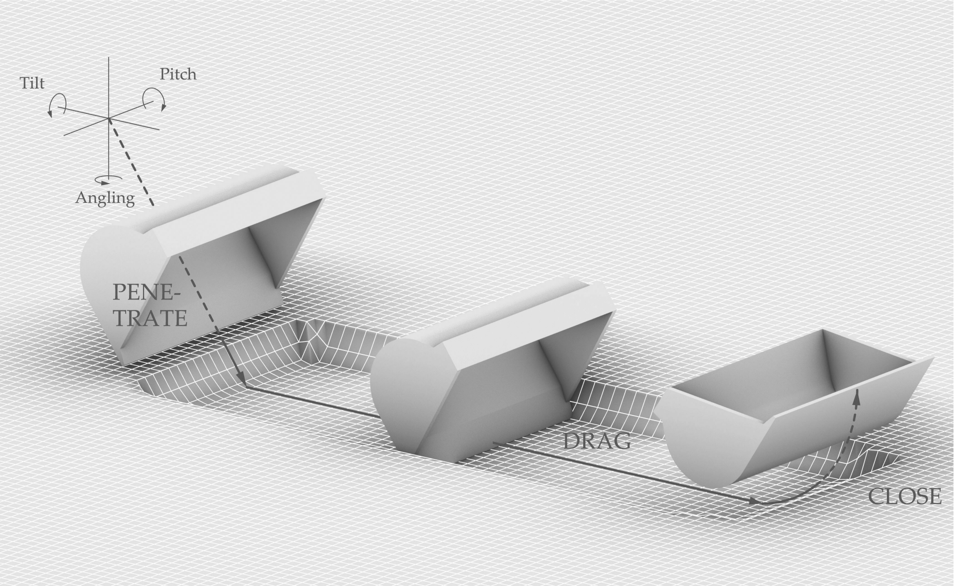


Figure 4.7: Example of a digging cycle in three steps: 1. penetrate, 2. drag, 3. close. Through the manipulation of the angle, tilt and pitch as well as the distance of each movement, custom shapes can be created by moving the blade of the bucket through a substance.

earth with heavy equipment. Though this list is not exhaustive, it provides a good overview of the manipulation approaches that were explored in the formation experiments. They consist of the *spreading* cycle, *digging* cycle, *dumping* cycle, and the *compaction* cycle. The spreading cycle operates with blades and pushes the material forward or sideways depending on the angle in relation to its forward movement. It is often used to strip or fill material to make a flat area. The digging cycle uses a bucket, as its movement is programmed to pick up material. Here, the front tip of the bucket makes the cut and defines the final shape of the excavation. The rounded back side makes it easy to close the bucket when it is still submerged within the soil. The dumping cycle drops the material out of the bucket. This can be done at a single location or as part of a movement over a larger area. This can become important when soil or gravel needs to be spread over a larger area. Finally, the compaction cycle provides mechanical strength within the soil, and is necessary for almost any sub-layers but not for the topsoil. It can be executed with rammers or rollers, by impact, pressure, vibration and kneading [37]. By separating the various cycles, a closer understanding of terrain modelling can be achieved. These earth-moving cycles have been explored in Section 4.3.

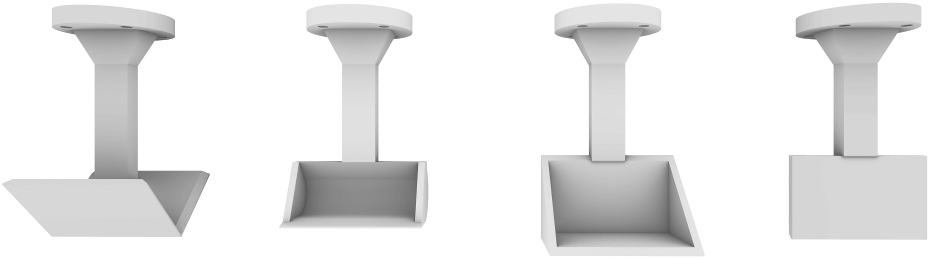


Figure 4.8: A selection of end effector tools that were 3D printed and used for the small scale formation experiments in a sandbox described in Section 4.3. Visible is the differentiation of the tools that are comprised of one, two, or four sides of a volume.

Tool Shape

There exist many earth-moving tools and accessories that can be used as end effectors on heavy equipment. Here we will focus on the actual shape—and movements of that shape—trough granular material. In terms of shape, we can distinguish them by defining a volume with six sides, where a typical tool will take up one or four sides of this volume partially or completely. This limits the possible outcomes of such a tool in the following ways; single-sided tools relocated material in the immediate vicinity of the cut, pushing it forward or sideways without picking it up, whereas four-sided tools will pick up the material and either dump it up on a pile or load it onto a dump truck to be hauled elsewhere. Examples of one-sided tools are the blades on dozers, scrapers, or graders which are capable of digging, hauling and spreading in a single working cycle. Shovels, and loading buckets used on excavators or cable loaders are examples of a 4-sided tool, where the material is picked up, hauled and dumped on a new location. The exception to this is the grading bucket, which can be used as a pick-up tool, as a pushing blade, and sometimes as a compaction tool as well. Of interest to the shaping of the material is the edge of the blade or bucket, though other parts of the bucket can start to influence the final shape when small movements or soil compaction are used. While the tool determines the possible final shapes that can be created, it does not respond dynamically to the found form and stays the same throughout the construction process. Instead, it is through the manipulation of its movement where terrain takes form.

4.3 Experiments in Dynamic Formation

With the development of HEAP, the full scale autonomous walking excavator by the Robotic Systems Lab of Professor Marco Hutter, it will be possible to shape large-scale natural granular material like sand, soil and gravel autonomously. The creation of a free-form topography using autonomous machines has never been tested before. To explore the potential of this novel construction process for landscape architecture, three design studios were initiated within the scope of this research as a collaboration between the Chair of Christophe Girot and Gramazio Kohler Research. They were carried out within a larger design question that is documented in Chapter 5. By combining a sandbox and small robotic arm and sensor technology, operation cycles were explored in model-scale to be able to test a wide variety of approaches quickly. For each design research studio, the operation cycle, end effector and material is varied, to be able to explore the design space of each method in more depth. Using the robotic mechanism, machine and material computation formed the central area of investigation and exploration. The work is validated for its potential of large-scale robotic construction and dynamic landscape design.

4.3.1 Experimental Approach

By combining a sandbox and small robotic arm and sensor technology, various operation cycles can be tested in model-scale. This was done to explore the combination of material computation and machine computation in granular material. This method was preferred as granular material set in motion may lead to many different outcomes, and final results can therefore never fully be predicted. By gradual adjustments of the robotic principles over many iterations, general concepts were be extrapolated. In the experiments, feedback determined the robotic movement to varying degree. In all cases, the simplest implementation takes the level of the sand, which determines the starting location for operations like penetration and subsequent dragging and closing movements.

Formation Principles

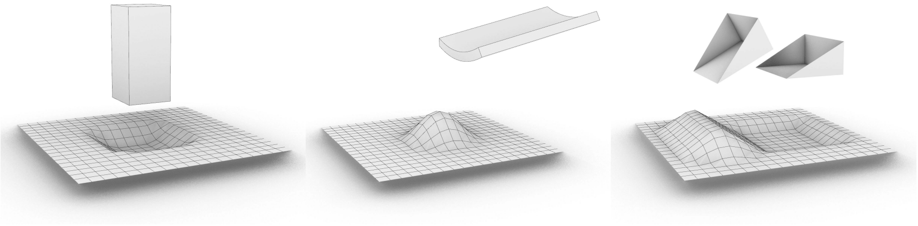
Leveraging the unique capability of a robotic construction method over automation or manual control, the design approach for the sandbox experiments focussed largely on procedural methods without depending on a predefined form. The dissertation distinguishes three approaches that are defined as a *procedural approach*, a *topological approach* and a *topographic approach*. In almost all experiments, both the topological and the procedural approach are used together. This is due to the fact that the digging cycles were mostly encoded as predefined motions, where only one parameter (like the starting point or direction of the digging operation) would respond dynamically to the topography of the sandbox. As the topographic approach is only explored in the robotic embankment prototype (see Section 4.4.1), a description of the design techniques for the procedural and topological approaches is given below:

- *Procedural Approach:* This approach can be described as operations that move earth based on rules, and involves a predefined performance goal. It does not rely on positions in space from the on-set. Instead, earth movements are determined by analysing the sandbox computationally (for instance to find high or low spots, slope orientation or other found properties). This approach does not create a repeatable geometric outcome, as a topography is unlikely to be exactly the same in subsequent experiments. Creativity originates from the emergent form that is generated by machine computation and material computation.
- *Topological Approach:* This approach can be described as operations that move earth towards a predefined topology without the need for a complete geometric description. As such, this structure does not have to be a surface but can also be point locations or a lines in space. It involves locations that are iteratively analysed to see if the goal is met. This approach results in geometries that are largely repeatable. Creativity originates from the emergent form generated by material computation.

On a cybernetic level, both the topological and the procedural approach can behave as a first or second-order system. A first-order system moves toward a predefined goal, whereas a second-order system can update its goal during the formation process. For the topological approach to become a second-order system, an adjustment of the predefined position-goal is necessary. To make this possible, the initial geometry has to be encoded parametrically to be able to change positions, dimensions, angles, or volumes. The procedural approach as a second-order system has to update its performance goals. The goal-adjustments can be implemented at any space or time scale (for example: after a single digging cycle or after many cycles by analysing the sand box as a whole). All the adjustments stem from an ongoing analysis of the desired state of the topography in relation to the current state.

Design Techniques

The experiments are aligned to established robotic excavation principles relating to operating cycles. In each experiment, both object (the tool) and context (the material) are varied (see Figure 4.9). The first experiments look at the *compaction* and *spreading* cycles, the second experiments at the *dumping* cycle while the third and last experiment explores the combination of the *digging* and *dumping* cycle. The cycles were applied to point locations in the box, either as a grid or relating to points on a set of curves. These locations were either manually defined or computationally acquired through analysis of the landforms in the sandbox. Because the operations rely on rules, its form only comes into existence in the sandbox. Therefore, only through iteration, one can start to comprehend what the rules are actually producing. By testing many alternatives in the adjustments of the operation cycles, it can start to show the designer how robotic processes relate to form. The topological transformations encoded as rules deform the surface condition of the material. In Chapter 5, these conditions were translated to a design on a real site and validated by computational simulation at the scale of the landscape.


(a) Spreading and compression cycle

(b) Dumping cycle

(c) Digging and dumping cycle

Figure 4.9: The operation cycles selected for the small scale formation experiments in a sandbox, where the digging and dumping cycle (c) combined the first two experiments (a,b) into a single cycle.

Design Setup and Workflow

Using the robotic mechanism, one complete cycle involves various hardware and software components to communicate with each other (see Figure 4.10). For the experiments, a Universal Robot UR10 was used, along with a 3D scanner (see Figure 4.11). In the first experiment, the end-effector was comprised of the Kinect V2 3D scanner, a force sensor and a tool holder to swap out various tool designs easily. The second experiment used a funnel and conveyor belt to feed the material, along with the Kinect for adaptive control. The last experiment only used the Intel RealSense 3D scanner along with a simple tool that was able to pick up and deposit material in a single movement.

To communicate with the robotic platform, COMPAS FAB was used within the Grasshopper environment of Rhino 3D. After an initial topography is made by hand in the sandbox, the 3D scanner captures the geometry as a large point cloud. This data is then filtered into a regular grid in orthogonal projection. The first and second experimental setup connected the Kinect camera using the grasshopper plugin Tarsier, while a custom script leveraged the remote communication protocol of COMPAS for the Intel RealSense camera in the third experiment. Here, all the filtering was done using the Python Numpy and Scipy libraries. The segmentation (to take out any points that fall outside of the working area), and localisation (data translation to match the world coordinate frame of the robotic setup) was achieved with Python and directly send as Docofossor-formatted data into the Grasshopper environment. At this point, the digital terrain model of the sandbox can be visualised in the Rhino viewport.

The analysis of the DTM resulted in parameters relating to elevation, slope and aspect as well as more complex computations that enabled a topological distinction of landforms like hills and craters and their distances. These were computed using either grasshopper or Python. These parameters would then determine the dimensions of the operation cycles, creating a dynamic response to the varying topographies in the sandbox. Through the combination of multiple cycles, a complete instruction set in the form of individual planes were sent to the robotic platform and executed. In the case of the first experiment, force-feedback during the execution could also influence the outcome.

Scale and Substance

The experiments were carried out in a sandbox. While the material properties and tool-size do not relate 1:1 to the real world, an abstract relation to full-scale robotic earth-moving can be established. Instead of a determined scale and accompanying technique, the experiments focus on procedural methods. This scaleless nature enabled exploration on both individual digging cycles but also on larger landscape formation processes. The materials used in the sandbox were varied in every experiment (see Figure 4.12). The first experiment used a synthetic modelling sand in order to test the expressive formal properties of a granular substance with high plasticity. The second experiment varied the grain size to explore the mechanical properties of terrain structures. Here, larger grains form a defence structure against natural processes in terrain. In the third experiment, a sandy substance in a mixture of clay, silt and sand was used. Depending on the moisture level, its properties change from loose particles to a substance with higher plasticity where the individual particles are bonded together. The difference in soil texture throughout the experiments changes the design space and call for diverse approaches in rule-based design.

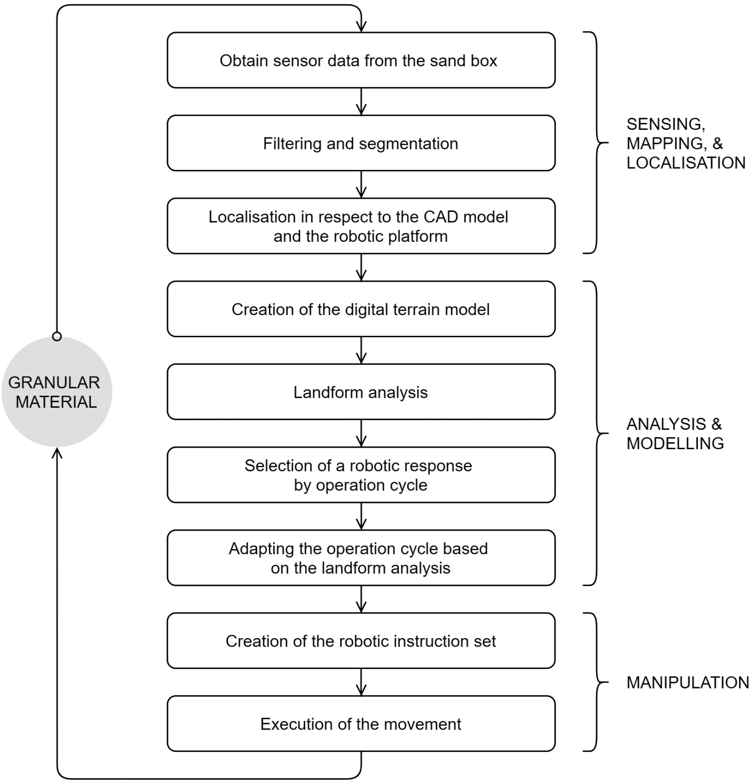
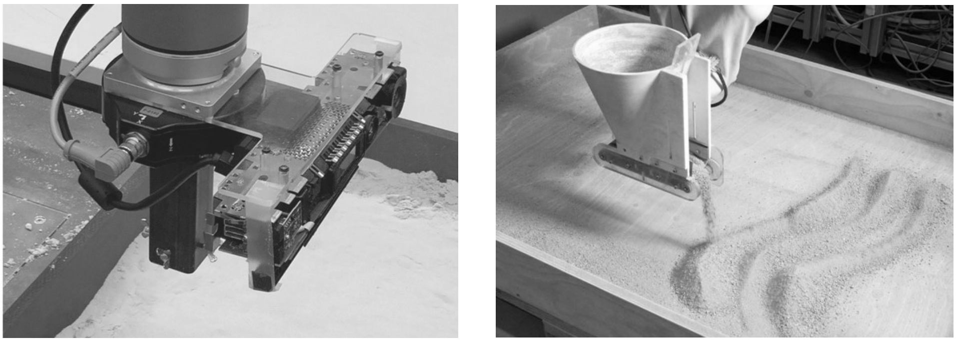
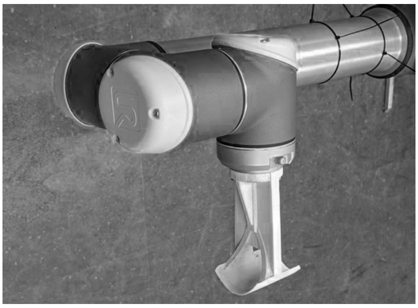


Figure 4.10: Flowchart of a typical robotic process in granular material of the formation experiments between the survey (sensing), design (modelling) and fabrication (manipulation).



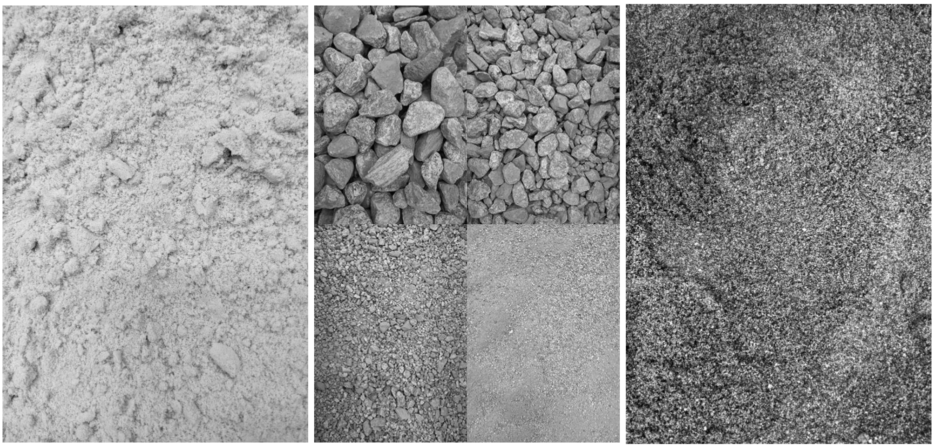
(a) 3D scanner, force sensor, and tool holder

(b) 3D scanner, funnel, and conveyor belt



(c) 3D scanner and modelling tool

Figure 4.11: End effectors mounted on a UR10 for the three consecutive formation experiments.



(a) Modelling sand

(b) Crushed rock

(c) Angular sand

Figure 4.12: Materials of the three formation experiments. The first experiment used modelling sand in a mixture of fine sand and wax (a), the second experiment sourced crushed rock from the site of investigation (b), while the third experiment used angular particles in a mixture of clay, silt and sand (c).

4.3.2 Formation Experiment 1: Spreading and Compression Cycle

The first dynamic formation experiment was held in 2017 as an integral part of the Robotic Landscapes I design studio. A linear and flat piece of land between a highway and river was destined to be transformed into a sound barrier and landscape park to provide leisure activities and shield the neighbouring villages from highway noise (see for the full description Section 5.4.2). In an attempt to reduce material transportation, volumes were kept in balance between digging and dumping cycles using in-place manipulation. The geometric composition of the terrain was the main area of investigation to increase the sound absorption by ground, screening, and reflection effects. To fulfil these requirements, a spreading and compression cycle was made possible by the robotic setup. A tool holder enabled the design of custom shapes that interacted with the sand, providing various imprints on the surface.

Geometry by Iteration

By leveraging the movement of the robot, it was possible to create complex surfaces with seemingly simple tool-shapes. This approach leveraged the endless possibility of tool movement over tool shape. In an iterative fashion, the sand was shifted and compressed. The shifting of the material provided the overall topology and structure for screening effects, while the individual impressions related more directly to absorption and reflection. Figure 4.13 show the design process over several weeks, where the structure was tweaked by changing the initial design line. This geometric 2D description was translated into a dynamic geometry in the sand using the force feedback sensor. The interaction between the tool and the sand created the initial elevation and starting point for the subsequent spreading and compression cycles. As such, this process is able to adapt to various initial topographic conditions. As the overall topology of the surface was achieved using a pre-defined geometric description that relates to a design intention based on landscape architectural properties of circulation and spatial qualities, the expression and performance of the surface was determined by movement rules in response to the initial state of the sandbox.

Local Transformation

As the site of exploration was long and narrow, it lends itself perfectly to balance material along the cross-section of the site. By defining a high-point somewhere along this section, the material on either side could be shifted locally towards this point. As such, the original volume stayed the same, while the topology and topography were transformed in order to perform on the level of noise reduction

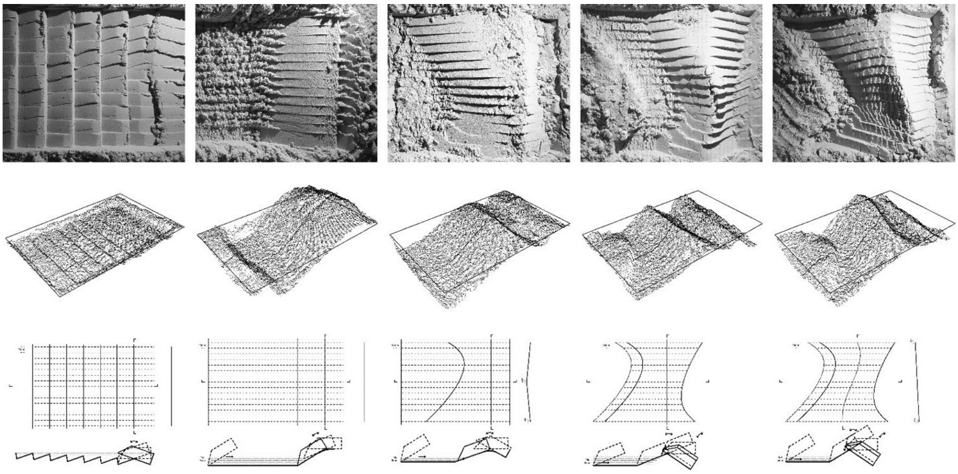


Figure 4.13: Design evolution by iterative adjustment of the spreading and compression cycle in relation to the design curve. The most bottom line of diagrams shows a single cycle, where the tool is moved back and forth in the material. The plan view shows the parametric relation between the distances and angles of the individual cycle, depending on the design curve. Following above are the 3D scans of the resulting topography and an orthophoto of the sandbox after cycle completion. By students Ladina Ramming and Thorben Westerhuys.

as well as providing access for people. This simple concept was translated into a combination of topological and rule-based operations. The centreline linking the high points were defined explicitly as well as the direction of movement, while the starting point was acquired using the force sensor as well as the amount of force needed for compression. As the amount of sand was kept the same throughout the operation, the final surface of the sand exhibited a purely local change though a topographic deformation.

4.3.3 Formation Experiment 2: Dumping Cycle

In 2018, the second design research studio Robotic Landscapes II explored the addition of material on a valley floor in relation to landslide and debris flow processes. The material was expected to arrive on the site by abrupt landslide events in yearly cycles. This material was not homogeneous, instead it resembled grain sizes from the smallest clay particles to large boulders up to 5 meters in diameter. The design task was structured around the re-distribution of material on-site to accommodate future material and direct it safely around the present villages. The robotic operation cycle involved the dumping of multi-granular material. This material was taken from the site and sorted into grain sizes relating to sand, cobbles and boulders between 0.5 mm and 5 mm to mimic the real world conditions

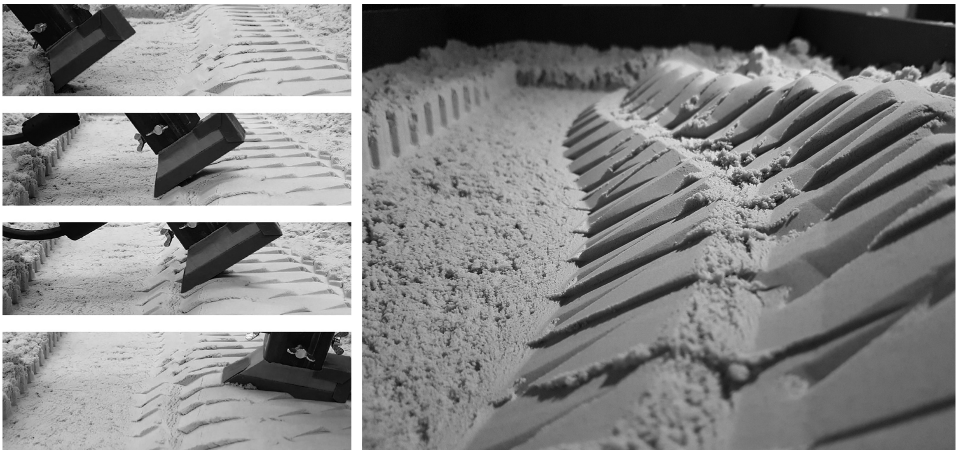


Figure 4.14: A simple end effector is moved through granular material using a spreading and compression cycle. By iterating over multiple locations with varying direction angles, a highly complex geometry can be achieved. By students Ladina Ramming and Thorben Westerhuys.

while still being able to deposit it with a small robotic arm. As the material scales do not translate well in a model sandbox, they were taken as abstract properties. The material was fed through a funnel and pushed out using a small conveyor belt to control the amount of material exiting the end effector dynamically. Again, a 3D scanner provided the technique to analyse volume change between the deposition cycles. As described in Chapter 5, Docofossor was used to translate the findings of the sandbox into a large-scale design, where it was tested using mass movement simulation for its potential in hazard remediation.

Material Interaction

As the first experiment used synthetic modelling sand, the second experiment focussed on the internal material computation of loose particles. The natural formation of sand depends on various properties relating to grain size and shape where angular particles can take steeper angles as rounded ones. Because the material was taken from the actual site of investigation, the particles were very angular in shape as they originated from rocks broken loose high above the valley. As the material computation in the box comes for free, any slope angle that is formed in the sandbox can be considered stable. Through the deposition of various grain sizes, a continuous surface could be created by stabilising the larger gravel using smaller grains. The various grain sizes influenced the roughness of the surface, which can potentially slow down natural processes on site.

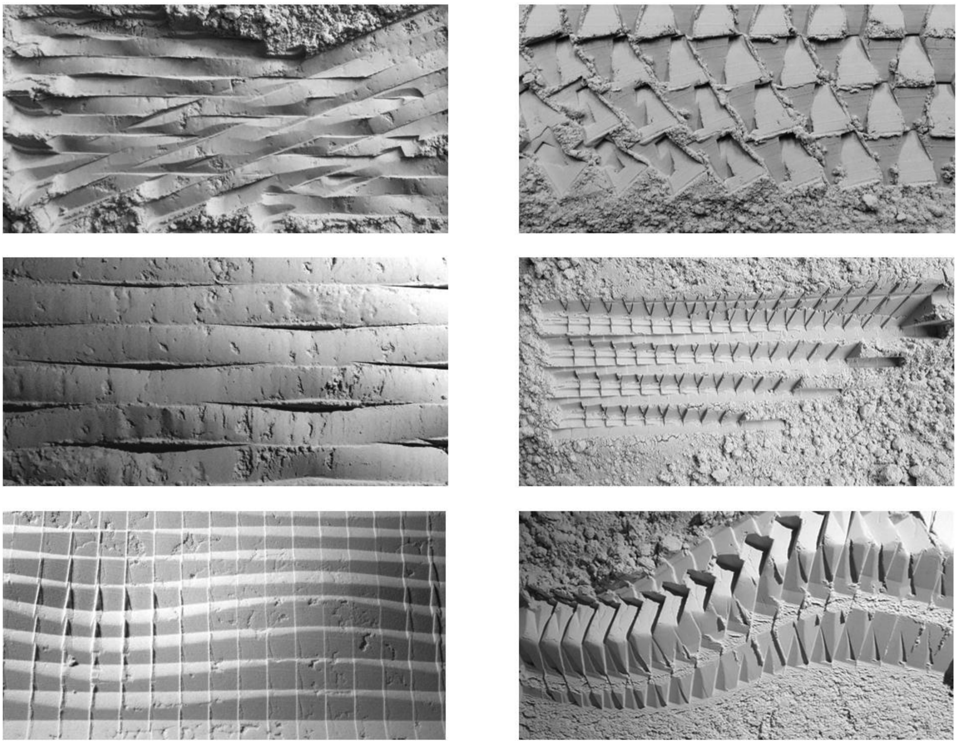


Figure 4.15: A selection sandboxes from the formation experiments applying the spreading and compression cycle in modelling sand. By students Michele Capelli, Maximilien Durel, Kenichiro Endo, Dominik Keller, Shohei Kunisawa, Abraham David Noah, Ladina Ramming, Laura Rickli, Thorben Westerhuys, Nicolas Wild, and Bing Yang.

Dynamic Aggregation

Through a process of iteration, the material was deposited into the box and analysed by height, slope and volume. In one proposal, a predefined height-goal was designed, and after each iteration, the topography was analysed to see if this desired goal was met. Here, elevation parameters from the sandbox were translated in speed values for the deposition: with a constant stream of material exiting the funnel, a slower movement of the arm resulted in more material that was deposited in the sandbox. This way, a predefined geometry could be achieved independent of the initial topography. This adaptive method does not necessitate an exact starting position, and the final topology can be responsive to any changes during the deposition cycle.

Landform Integration

By analysing the initial topography of the sandbox, landform features can be extracted as locations or regions defining a specific topological surface. This can relate to hills, craters, or more specific properties relating to grain size. Once these features are defined, a specific topological response can be encoded. As large boulders were expected to be deposited on-site, it is economical to integrate them into the design as it takes much effort to transport them to a new location. Figure 4.16 displays the process of finding existing boulders, creating nodes and relations between them, and finally depositing material in such a way that it can perform on the level of hazard remediation by redirecting debris. By defining an overall goal and specific topological response, existing landforms can be integrated without the need for designing a predefined and static geometry specifically.

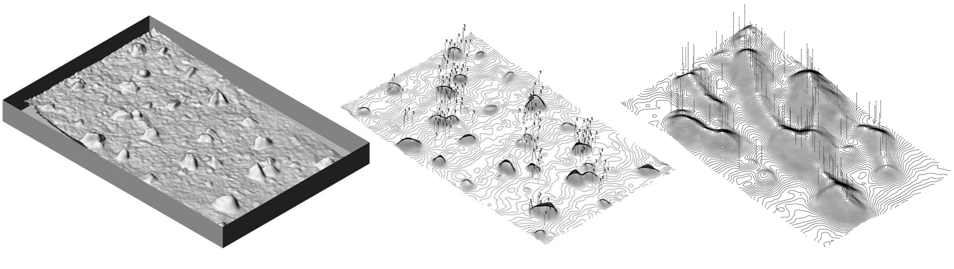


Figure 4.16: Example of a robotic feedback mechanism: the first image displays the starting point as sensed by the 3D scanner. From here, the topography is analysed, and landform nodes are established that get connected together based on slope direction. The last image displays the sandbox after robotic deposition around and in between the nodes, integrating the initial features into a topology capable of directing material flow. By students Kelly Meng and Dawit Tadesse.

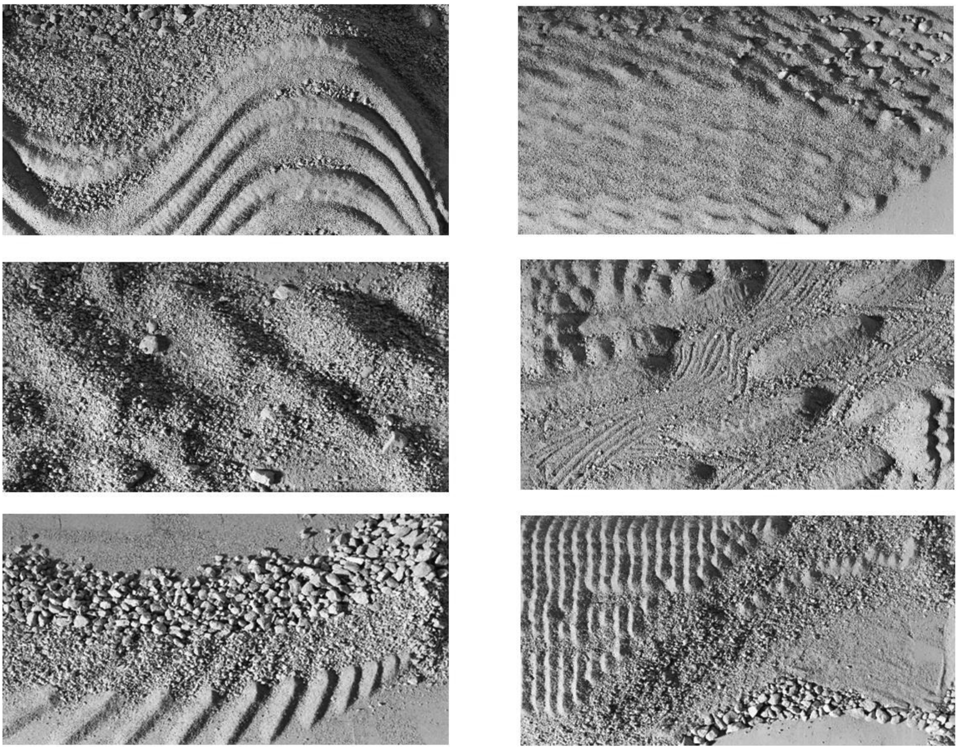


Figure 4.17: Overview of six sandboxes form the dumping cycle experiment, by students Andrea Calzolar, Rongsheng Chen, Kelly Meng, Lip Jiang Lee, Matthew Lee, Elizabeth Levy, Sebastian Meier, Sam Mettraux, Stanislaw Modrzyk, Carlo Molteni, Cilgia Salzgeber, Gereon Sievi, Yorika Sunada, Dawit Tadesse, and Ayako Yamagishi

4.3.4 Formation Experiment 3: Digging and Dumping Cycle

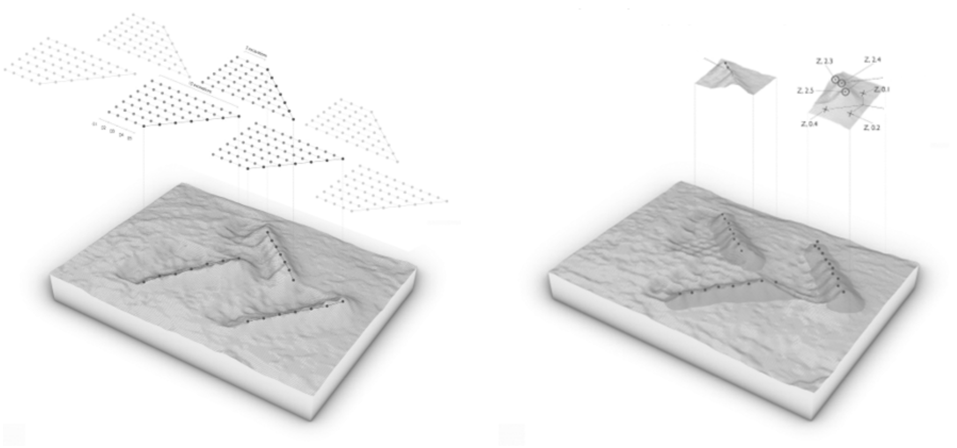
While the first two experiments separated the excavation or the deposition cycle, the third experiment was designed to explore its combination. The tool shape was kept as abstract and simple as possible, allowing the motion control to explore the material distribution and geometric complexity. The chosen site for the larger design question dealt with a continuous stream of material spilling out of a gorge onto a debris cone. Due to erosion and deposition, the material balance within this stretch of river will never be in equilibrium due to the land use of neighbouring farmland and villages. Natural hazards in the form of floods and debris flows are bound to occur indefinitely unless a continuous material strategy is applied. Through dynamic formation, the design exercise explored maintenance strategies that mitigate natural hazards by leveraging robotic processes and erosion and sedimentation processes. The analysis of the sandbox was achieved using Docofossor, where the difference in volume and elevation could easily be tracked throughout the operation cycles.

Dynamic Distribution

Strategies were developed to accommodate the re-distribution of eroded or deposited material due to natural processes on the site of investigation. Here, materials were moved robotically towards a certain position based on landform characteristics. In the sandbox, strategies were implemented by analysing the elevation and the aspect of the topography. Depending on the strategy, the material was moved downhill or uphill. This was applied in a simple grid of points, or along a design line where the topology of the final outcome would achieve a specific structure in response to the natural processes. It formed a second force in the sand, capable of steering or opposing natural processes.

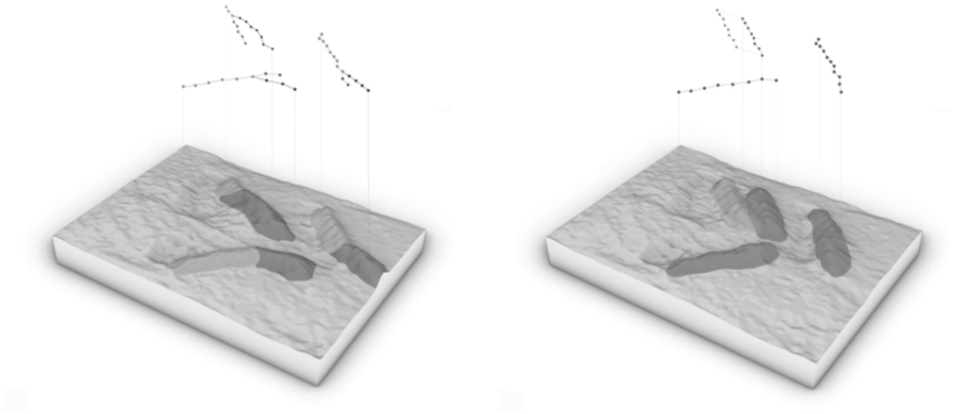
Goal Optimization

It is hard to simulate erosion in the sandbox as the physics in model-scale do not translate easily to large landscape processes. To gain an understanding in how a rule-based processes would respond to erosion, the sand was moved around in the sandbox manually. As a specific elevation or topological goal was achieved by moving sand with the robotic process, a manual change was made and re-evaluated through analysis. In turn, the robotic process recognises that the achieved goal was no longer valid, and would start to move the sand back to its desired end-goal yet again. As such, natural processes can be controlled in an iterative fashion, were the robotic processes only interfere in case of a failed performance analysis. Volume goals were set as well, that could alter the topology to look for the smallest material movement possible (see Figure 4.18).



(a) Initial construction: Creation of the dam structure where the elevation relates to the amount of available material behind the dam.

(b) Landform Analysis: Detecting location, aspect and elevation of dam structures by combining neighboring high points into a ridgeline.



(c) State Comparison: Analysing the change from an initial to a new state as formed by natural processes and deciding for a course of action.

(d) Update Final Goal: Two dams were maintained in their initial position while a third was shifted to minimize material transport on site.

Figure 4.18: Robotic process demonstrating a topological state-goal change by analysing the initial and current topography of the sandbox, by students Casper Trueb and Lorin Wiedemeier.

Responsive Geometry

One of the more exciting aspects of dynamic formation based on found material properties is the emergent behaviour of a rule-based system. Due to the chaotic structure in terrain, a robotic response changes ever so slightly depending on the analysis. By encoding the movements based on the existing terrain, an unforeseen and emergent new form arises. While this was mostly in relation due to material computation in the sandbox, when combined with natural processes a new choreography can originate in the terrain. As long term simulations were hard to achieve in the sandbox, these concepts were explored in the large-scale design proposals as discussed in Chapter 5.

Open Ended Formation

As natural erosion and sedimentation processes in terrain will continue forever, the robotic formation can continue to respond to it as long as it is kept in operation. Due to the dynamic nature of both natural and robotic processes, it is hard to foresee how these processes will interact over a long period of time. However, there were experiments that tried to understand how open-ended formation principles could be implemented. One such case related to the ability of a surface to slow down and store material. Here, hills and craters were created in the box that would re-distribute themselves automatically, with a bias of higher hills and lower craters towards the centre. This rough surface related to the larger design intention to cause water and debris flows to slow down and settle in the lower areas. This natural process would in turn flatten and smoothen the terrain. As a result, the mechanical movement of the material, as defined by responsive rules, created yet again a rough surface by digging and dumping. A never-ending process was created maintaining a performative topology in terrain.

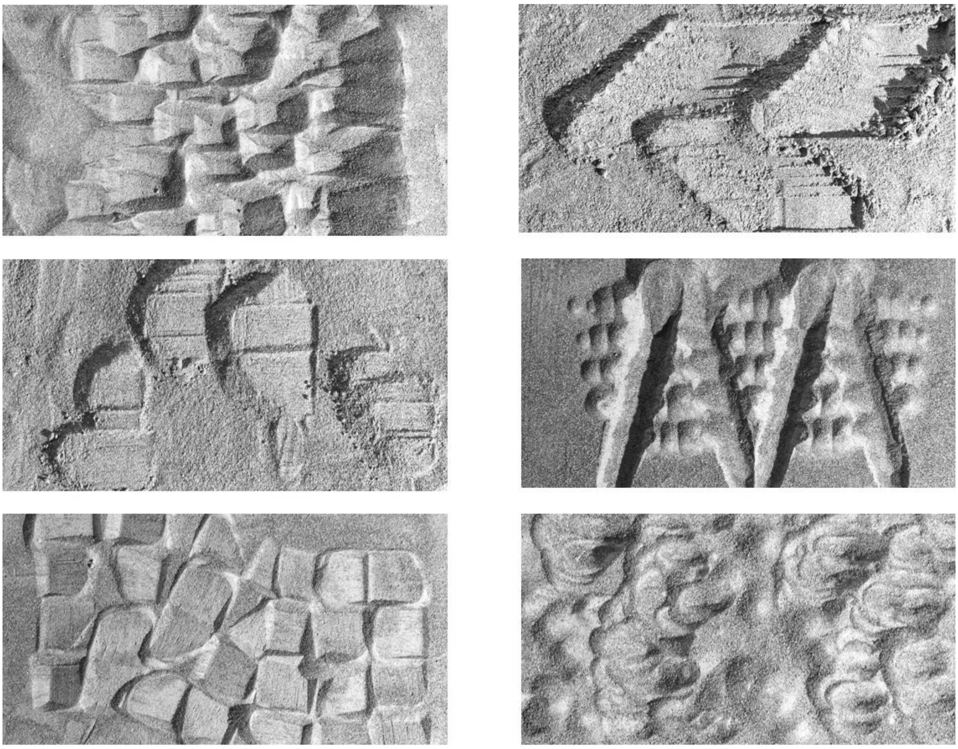


Figure 4.19: Overview of six sandboxes form the combined digging and dumping cycle experiment, by students Leon Beck, Tobias Etter, Nicola Graf, Leo Graf, Mathias Häcki, Hannah Kilian, Yuki Minami, Sakiko Noda, Zehra Ter, Caspar Trueb, Lorin Wiedemeier, and Matteo Zwyssig.

4.4 Robotic Embankment Prototype

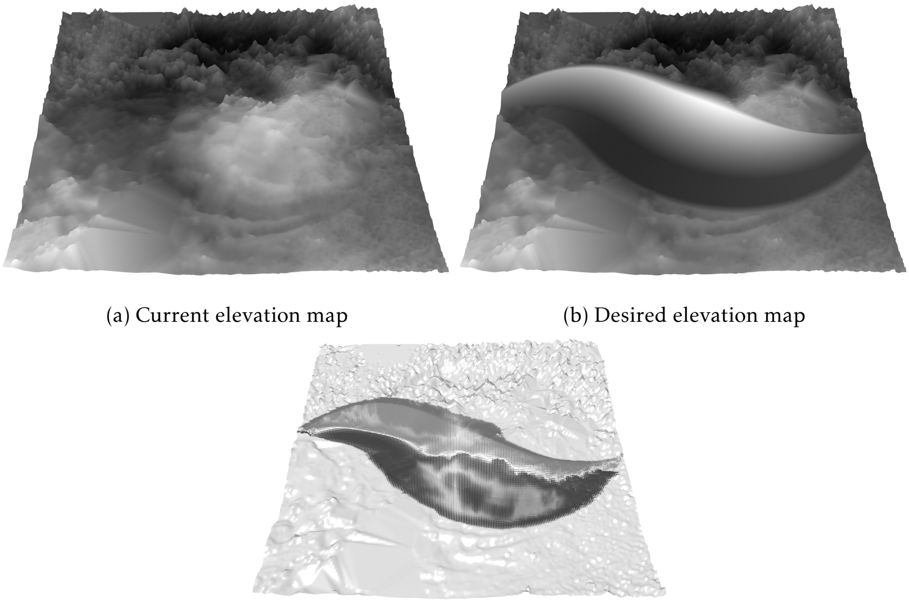
This real-world embankment prototype results directly from the interdisciplinary research approach within the NCCR Digital Fabrication, ETH Zurich. It is part of the On Site Digital Fabrication research stream focussing on Construction Robotics. The aim of this research project is to develop novel technologies that enable robotic, architectural-scale and landscape-scale building processes with a focus on natural or recycled material. This particular demonstration comes forth out of the collaboration between the Chair of Landscape Architecture of Professor Christophe Girot and the Robotic Systems Lab of Marco Hutter. It was executed in summer 2020 by the author and PhD researcher Dominic Jud. While the author of this dissertation focussed on the design and its tools, Dominic Jud developed novel control concepts and planning algorithms to overcome current limitations in autonomous excavation. Building upon the implicit terrain modelling tools from Chapter 3, this particular experiment aims to develop new tools and processes to establish a direct connection from the design to the fabrication environment of HEAP, which in turn enabled the realisation of free-form geometry in terrain on the NCCR Digital Fabrication test field. By using implicit terrain modelling tools and implementing a robotic fabrication framework, a direct link is established between design and execution environments. This allowed for feedback and easy adjustments of the desired topography during operation. The following paragraphs explain the methodology, implementation, and results in more detail.

4.4.1 Methodology

The methodology of this robotic embankment experiment relies on the robotic mechanism between surveying, designing and fabrication. The preparation involved the survey of the test field using both mobile and aerial lidar systems. The aerial survey was used to design the base topology, calculate cubature, and generate the desired elevation map.

Design Approach

The design was achieved using custom modelling components based on Docofossor. Here, material, progressive, fabrication and topological constraints were taken into account. The slope of the embankment was set to 33.7 degrees and the total volume displacement at 30 cubature. Though it could have been made steeper due to the silty clay on site, the expected rain encouraged this conservative approach. The position of the embankment was set to minimize erosion within the swale in front of the embankment, to enable access for HEAP, and to make maximum use of the topography within the site. The embankment in the form of an s-curve demonstrates the free-form modelling capabilities of HEAP and establish a relation to landscape architectural design as a topographic divider of flows. The shape was encoded using distance functions on a path curve. Here, a generative sine wave algorithm established the overall topography, which was adjustable in all dimensions by amplitude, wave-length, slope, width, height and depth parameters. The final design was composed to follow the general slope of the site, catch any water runoff in the swale, stay within the workspace of HEAP, and accommodate a single motion path on the terrain by adjusting the respective parameters.



(a) Current elevation map

(b) Desired elevation map

(c) Cut and Fill

Figure 4.20: Illustration of the current and desired elevation maps before execution, including a cut and fill diagram, from the design environment. The design is encoded using distance functions on the elevation map while balancing cut and fill using a swell factor of 1.05, based on a single freeform design curve.

Formation Approach

The robotic formation approach is distinctly different from the small-scale formation experiments described in Section 4.3. While the planning and control algorithms on HEAP are inherently procedural by evaluating the digging and dumping locations in every cycle, the connection to the design does not rely on purely procedural or topological descriptions. Instead, a topographic shape description in the form of an elevation map used to determine the digging motion

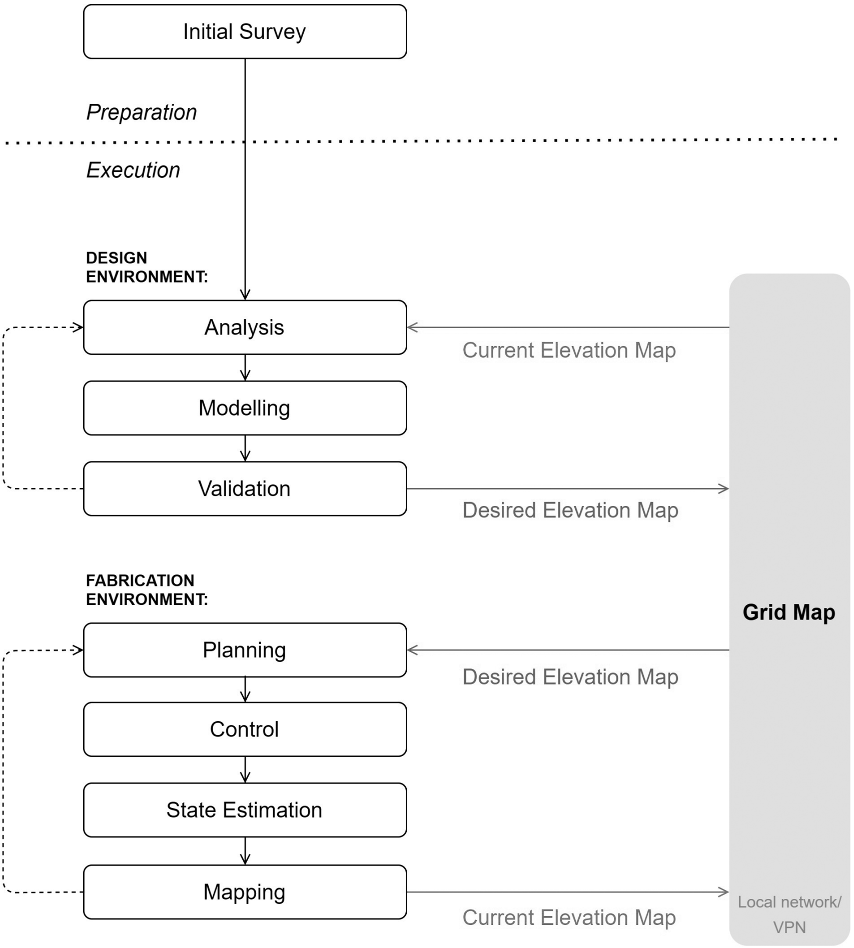


Figure 4.21: High level overview of the integration of the survey (Aerial Lidar System, Mapping), the design environment (Docofossor with COMPAS FAB), and the fabrication environment (HEAP) using the current and desired elevation maps.

and dumping location. This was done to build upon previous work in planning and control by Dominic Jud [12], and to explore the capabilities of Docofossor to communicate with Grid Map using ROS messages. Here, at any point in time, there exists a current, and a desired elevation map, from which all the dynamic behaviour originates. It allows dynamic design and fabrication processes to happen asynchronously. As the robotic environment iterates very fast, it allows the design adjustments and evolution to operate at a much lower rate. As an outline of procedural and topological approaches is given in 4.3.1, below follows the description of the topographic approach:

- *Topographic Approach:* This approach can be described as operation that move earth towards a predefined geometry. It relies on the continuous analysis of the difference map between the found and desired elevation. The robotic movements are based on the desired geometry; dynamic and responsive behaviour do not rely on the found geometry but can only be inscribed in the design environment. Creativity originates from the desired geometry based on machine computation.

This was implemented using the COMPAS FAB extension of the COMPAS framework, and the roslibpy library, both developed by Gramazio Kohler Research. While the elevation maps use Grid Map to send, store, and receive messages, a geometry message was used to send the base design curve to the fabrication environment in support of path planning purposes (see Figure 4.21).

4.4.2 Results

The experiment lasted three days in total, but had to put on hold for a day due to heavy rain. The cubature approximation in the design phase used a 1.05 swell factor which proved to be reasonably accurate, as there was no need to update the desired geometry during execution. However, the rain created a muddy path for HEAP to drive over, which caused challenges at the edge of the swale. As the desired elevation map was encoded algorithmically, it was straightforward to update the map in this area to prevent the wheels of the excavator from sliding into the swale. The rainstorms during execution erode the precise final geometry but not enough to warrant readjustments. As the experiment was recently completed in summer 2020, it will be interesting to follow the erosion of the embankment over a more extended time period. While the grammar of earth-moving, as described in the formation experiments of Chapter 4 leveraged the expressive potential of a robotic movement through a substance, this experiment focussed on demonstrating the creation of a precise geometry. As such, the influence of 'shape' and 'motion' of the robotic platform was not a goal, but became apparent in the southern convex corner. Here, the straight edge of the grading bucket was not able to reach into the tight curvature of the desired geometry.

(a) Digging cycle

(b) Dumping cycle

(c) Fabrication environment

(d) Aerial view during execution

Figure 4.22: Execution of the prototype with HEAP. Figure (c) by Dominic Jud.

Figure 4.23: Orthophoto of the final geometry of the robotic embankment prototype.

4.5 Summary

Dynamic formation in granular processes depend on the elements of the robotic mechanism. This enables a direct link between the material at hand and robotic instruction. Based on the experiments, a beginning has been made with a constraints description for robotic landscape fabrication following the first two core concepts of dynamic formation relating to material and fabrication constraints. This description is complemented in the next Chapter by progressive and topological constraints. The relevant variables for terrain are categorized between the angle of repose, the texture and horizons of soil, and the consolidation belonging to volume balance. For fabrication, a platform-independent description is understood as belonging to motions and shapes that together define the grammar of earth-moving. By linking found terrain variables to the motion of the end-effector, a new topography can be formed. This has been explored using parametric descriptions in various combinations of procedural, topological, and topographic approaches. These dynamic formation processes describe a rule-based transformation of the natural granular material that is informed by landform analysis. This enables an adaptive, emergent and open-ended process, which are presented in their potential for large-scale earth-moving.

As the digital techniques of the robotic instruction were developed mostly before Docofossor, the small-scale experiments did not benefit yet from the integration of implicit modelling methods. Instead, they were specifically geared towards the specific project and concept, where individual point analysis translated to robotic movement. This allowed students to come to grips with all aspects of the robotic feedback loop. However, it also meant that the approach did not include a full surface topography, but rather, related to single points or lines. As such, their procedural and topological character was better understood than their formal (topographic) counterpart. In consequence, it turned out to be challenging to overcome the problems of scale and texture, which rendered the sandboxes less formal and more inspirational towards the understanding of robotic processes in terrain. This was intensified by the homogeneous material profile throughout the experiments, which is far from the reality in actual terrain.

By designing digging cycles relating to spreading, compression, digging or dumping, it was straightforward to create many operations along a line or on a grid. The starting point, angle, and direction of the cycle is determined by the analysis, which creates small variations within every cycle that is specific to its respective location in terrain. This resulted in various strategies for robotic earth-moving, relating to geometry by iteration, local transformation, material interaction, adaptive aggregation, landform integration, dynamic distribution, goal optimization, emergent geometry, and open-ended formation. By using only found material, and modifications that are tailored to local conditions, a site-specific and adaptive formation approach was made possible. The online adaptation of the design based on ongoing insights during the formation process is therefore able to respond to changing site conditions throughout scale and time. In the small-scale experiments, procedures were automated to various degrees.

The robotic embankment prototype showed how design and fabrication in terrain is influenced by material and fabrication constraints. In evaluating every future dig or dump based on the current condition in terrain, HEAP is able to respond dynamically to changes in terrain or changes in the desired elevation map. While the natural processes acting on this embankment in the form of rain were relatively minor (and there was little need to act on them during execution), the dynamic construction approach on HEAP proved to be robust. The integration of survey, design, and fabrication was enabled with tools developed in this research and the developments on HEAP. While manual tasks were still present in this demonstration, a increasingly autonomous design and construction approach in terrain is ready to be explored. As such, future experiments can leverage this setup to fully incorporate dynamic design strategies in larger terrain structures.

Dynamic formation processes in terrain leverage material and machine computation. By parametrizing the digging or dumping cycle, individual movements of the end-effector get informed by the material system itself. Using topological rules in landform analysis, the relations that exist in surface structures can be understood and acted upon. As the topography of the loose and granular material collapses and settles in an unpredictable way, the robotic mechanism continuously re-interprets and reacts. This dynamic construction process is therefore well-positioned to respond to the dynamic nature of terrain. While a first-order cybernetic system strives towards a pre-defined goal, and can respond dynamically to an unexpected change in terrain, a second-order cybernetic system can evolve together with the natural system. The dynamic evolution of landform is therefore not understood as a mere topography, but finds its formal expression from the underlying topology void of dimension. This enables the creation of a dynamic topography that is able to shrink or grow without losing its structural intelligence. Now, emergent and open-ended processes are encouraged to take form by material computation. Through the robotic earth-moving grammar of shapes and motions, a poetic dimension of the underlying form can be brought to its surface, creating design opportunities for performative structures and expressive formations in granular material deeply rooted in the intelligence of local terrains.

Chapter 5

Form and Forces: Dynamic Design in Terrain

> *My ultimate aim, however, is more radical: [...] it is to overthrow the [hylomorphic] model itself and to replace it with an ontology that assigns primacy to the processes of formation as against their final products, and to the flows and transformations of materials as against states of matter.*
>
> —Tim Ingold [34, p. 93]

5.1 Overview

Robotic landscape fabrication is still a very new construction technique, and its potential for large-scale landscape design has rarely been investigated (see Section 2.3.3). In light of the ever-increasing pressure on ecological and urban systems due to climate change, causing damage to both natural and cultural landscapes, this Chapter explores a dynamic design and construction approach to mediate future deterioration and hazards. While Chapter 4 explored robotic fabrication in natural granular material which resulted in new formation strategies in terrain, this Chapter looks at the design of large-scale landscapes that proceeded in parallel to the physical experiments in the sandboxes. To evaluate the potential of robotic landscape fabrication, three case studies are explored and described towards the end of this Chapter. During these design experiments, the research recognised that robotic construction processes mediate and direct natural processes in large-scale landscapes. The experiments demonstrate various applications for robotic landscape fabrication, assessing architectural potential through diagrams and drawings and validating its performance by simulating natural processes in terrain.

The Chapter starts by outlining the dynamic design processes of robotic fabrication in natural environments. This is followed by an overview on form and forces in terrain. Here, form is understood on two levels; topology describes its order and relations while topography represents its dimensions in space. The forces in terrain are twofold as well; natural and manufactured. The natural processes consist of debris and water flows, while the human-made forces are explained through the lens of a dynamic earth-moving grammar. These two forces complement the four core concepts of dynamic formation in terrain: substance, process, grammar, and form. Together, they describe the design space in terrain that is subsequently defined as material–, progressive–, fabrication– and topological constraints. All four concepts are equality considered in the explanation of the dynamic design system, which highlights the methodology of the design experiments in this Chapter. It builds upon the computational terrain modelling tools from Chapter 3, and on procedures using the robotic mechanism from Chapter 4. These methods should enable designers to experiments with adaptive, emergent, and open-ended design concepts while staying within a valid and performative solution space. Finally, the design experiments explore a dynamic response in dynamic environments to enable a local and resilient approach in working with the terrain.

5.2 Design processes in Dynamic Environments

To come to valuable solutions in terrain, a thorough understanding of natural processes is essential. This cannot be achieved by applying expert knowledge alone, but involves performance testing, as each site and design solution has an inherently specific form and process. Here, quantitative observation is as valuable as qualitative insights. Reflexive design processes can mediate between the intent of the designer, forces of nature, and the robotic agency in the landscape. Due to the complexity of finding a valid design solution, computational methods can provide tools to describe and constrain various actors in terrain. Already in 1964, Christophe Alexander recognized this potential in by proposing an analogue program to explore the conceptual order which of problems presented to its designer [19, p. 7]. By following topological methods, the form of terrain can be described as relations and proximities in surface structures. This allows the final form to depend on parameters coming from the material system, natural evolution due to mass movement or hydraulic processes, as well as the robotic movement of an excavator-bucket. The following sections will expand on these concepts, offering the foundation for a dynamic design approach.

5.2.1 Dynamic Design

Reflexive Design Processes

Dynamic design is characterised by constant change, activity or progress [141]. It relates to the underlying cause of change and is often connected to technology as robotic systems or performative structures. But it also relates to landscape architecture where environmental forces like wind and water act on terrain and setting it in constant motion. Designing for a dynamic construction process within a dynamic environment poses several challenges on design methods and its medium. Digital design is the only medium that enables the incorporation of dynamic systems within a design process on a large scale. Oxman [142] provides four classes of interaction between the designer and digital media: paper based, digital, parametric, and computational representation. Here, only the computational may hold a truly dynamic system where the outcome cannot be predefined by a set of parametric rules or relations. As natural and robotic systems evolve over time, computational methods become the foremost and essential tool to understand and design within dynamic systems. This is true on a qualitative level in terms of formal expression of terrain as on the level of performance, how it functions.

Designing within a dynamic system changes the role of the designer [68, p. 130]. The close connection between digital models and natural environments, established by robotic fabrication and computation, leads to design chains were the final product is not a static object but part of a continuous formation process. Instead of complete control over the outcome, a designer has to interact with digital media in terms of moderation by directing the flow of forms and forces. As such, the designer becomes part of the system as the mediator of culture between robotic and natural processes, where each have their own internal logic and constraints. The interactions between a designer, a robotic response, and a physical environment in design can be theorised as a reflexive design process [143]. This is not a fully formed method but rather a collection of design and research tools relating to creativity and knowledge building. Schon summarises the creative process as recursive and reflective between framing, moving and evaluating [144, p. 23]. As mentioned in Section 1.3.4, this entails setting the problem and objective, exploring and proposing solutions and finally looking critically at the result, which in turn leads to a re-framing of the problem and objective where the cycle can start again (see Figure 5.1). In the recursive application of the robotic mechanism, a future move is determined by analysing the current state of the system. This self-referential loop can be guided by a reflexive design processes, where second-order cybernetic systems can be envisioned and evaluated.

Figure 5.1: Reflective process of design as an iteration between framing, moving and evaluation. Taken over from Schon [145, p. 39].

Dynamic Design Methods

In dynamic design, reflective or recursive methods are particularly useful to model—and continuously evaluate—evolving systems over time as empirical experiments. As the outcome of a dynamic process is unclear, it needs to be simulated over and over again to gain insight into its future evolution. This process is more commonly referred to as form-finding or form searching [129]. As displayed in Figure 5.2, the dynamic design process can now be described by iterating over three main steps: *Framing* brings together all the constraints that operate within the material, the robotic platform, the natural processes in terrain as well as the landscape architectural objectives. These are subsequently encoded to form the basis of the design space and modelling operations. *Forming* is the action itself, the transformation of the digital model, either by explicitly encoded geometry or using parametric methods. *Finding* finally relies on computational methods that can simulate natural processes acting on the modelled form. As such, it is not about predefining a form, but rather the search for form under the influence of natural processes. As the system evolves, the design constraints can be updated based on the results of the simulation. This process can be automated to various degree, leveraging digital methods to inform the designer on the outcome of the design interventions. In Section 5.3 each step is explained as a technique of dynamic design in terrain.

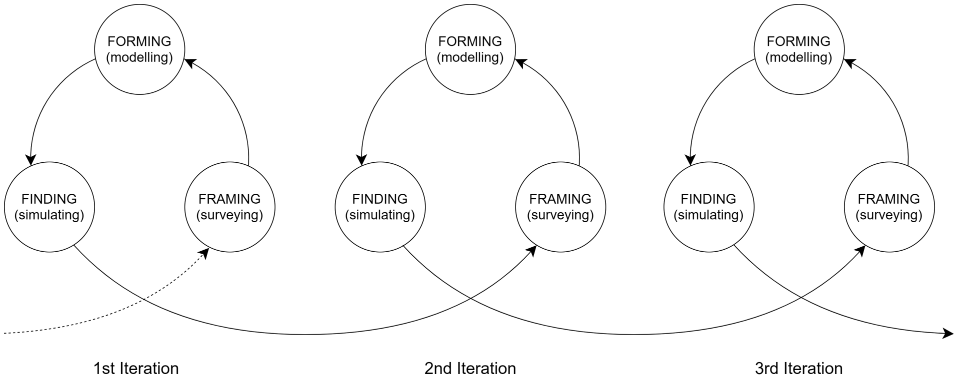


Figure 5.2: Process diagram of reflexive design. By iterating between framing, forming, and finding methods, insights in the evolution of dynamic systems can be acquired.

5.2.2 Form: Topology and Topography

The encoding of geometry using implicit methods enables a modification of a surface without the need for Boolean operations on explicit geometry in mesh or NURBS format (see also 3.3.2). To explore designs on a formal basis while allowing for dynamic form generation, the use of topology is considered as a formative method. Now, the form of terrain can be encoded using topological descriptions of landforms that result in topographic form using implicit modelling methods. We will follow the duality between topology and topography as defined by Bernhard [122, p. 24]. Here, topology is understood as a network of structural relations in terrain while topography is defined as its position in metric space. As such, topography always has a topological component, while topology can exist on its own. In his research *Domain Transforms in Architecture* Bernhard [122] explains it as follows:

> *This duality is about elements and their relations among them. Elements can be anything, islands in a river, vertices in a mesh, bones in a skeleton, rooms in an apartment or data points in a table of an enterprise's customers. Topography looks at their position in space, invariant to changes in their relations. [...] Topology looks at the relations between the elements, their connectivity, invariant to changes in their metric position. A metric space is a particular case of the more general topological space, namely one*

> *that allows measuring distances between two points. [122]*

The topology in terrain is more ambiguous than its mathematical counterpart. Defining an island in terrain depends on the level of the water, however, its topography is actually continuous. We can use existing landform categorization methods, where nodes and their relations can be defined. Here, landforms are distinguished in mountains, craters, ridges, valley, berms or swales, e.g.. Topography, on the other hand, is more familiar to us, and describes the position and dimension of each node. To understand how we think of this duality in terrain, we can distinguish *amount of nodes and their relation* (topology) and *shapes and their dimension and position* (topography). Below follows a description of each.

Topology

Topology is generally considered as the relational structure in surfaces in the field of mathematics. As a design method for landscape architecture, it denotes the topological approach as defined by Girot et al. [11] that sets forth a theoretical position and practical method (see also Section 2.2). While this method is defined more generally, we will look at its implication for terrain specifically. Here, terrain structures (natural or manufactured) are considered through their (1) symbolic and aesthetic dimension as well as their (2) relations that exist within site-specific surface structures at all scales. Here, we will look at the second definition of topology closely linked to its use in mathematics. To analyse and create relations within the terrain, a multitude of quantitative tools can be applied that have been developed in the field of geomorphometry. Classification and modelling of terrain benefits from a descriptive method that looks not only at its position or dimension in space but also how they relate to each other: topological space. Here, elements can be ordered according to necessity: *"...bringing together diffuse fragments and shaping them into a meaningful, liveable structure."* Girot et al. [11]. This topological approach to terrain has become especially important with the recent focus on ecological mapping and environmental planning [146]. In dynamic natural systems, topological descriptions can inform the continuity or discontinuity of water and earth movements. More strategically, it provides a relational model between the *form* of terrain and their *processes*. Practically, it provides ways to describing landform as a dynamic system without having to resort to static topographic descriptions over time.

The power of a topological methods in digital design has been described by Oxman [142] as follows: *"[...] topological design may be seen as characterising the first formal statements in a new design philosophical worldview that attempts to accommodate the new complexity of non-linear, networked conditions, and to depart from the more static and typologically deterministic logic and design methodologies of the previous generation."* As such, it can provide tools for dynamic design in terrain by leveraging parametric and computational tools, without losing control over desired formal qualities. A topology network in terrain can be described as nodes that are linked together by a relation (or in geometric terms as vertices and edges). Examples of nodes are mountain peaks and craters, flow divergent and convergent points in streams, or areas with similar properties like the aspect of terrain or its soil type. These nodes can then acquire a relation to each other using a network graph. Each link in the network can have many attributes like directions (in case of a watershed graph), or a weights (for instance the proximity of nodes).

Analysing landform based on topology has found many applications. These methods are based on topological data analysis and operate directly on a DTM, though some tools provide algorithms for mesh networks as well. On an abstract level, terrain representations are used as a metaphor to visualise scientific data. Here, a landscape is given the same topology as a given dataset of an n-dimensional scalar function to make its information intuitive and accessible [147]. On a more practical level, it has been applied in geospatial analysis of structures like ridge-lines, valley networks, or watersheds [148]. Some of these methods are freely available in GIS software as topological operations to understand relations between points, lines or regions where analysis include adjacency, containment and proximity. This analysis is particularly important to test for topological continuity when coordinate space is deformed by projection into another coordinate system. In remote sensing, a topological method can help classify land cover by grouping and separation of local features [149]. In all these methods, scale plays an important role. Small scales relate to smoothness or roughness of a surface, medium scales determine relations within embankment structures, terraces or swales, and at large scales, the overall shape of the landscape is understood between mountains and valleys.

A topological method in terrain, how its structure acquires form and how this informs processes acting on it, is essential to start to model it. This does not relate to the many applications that deal with systems thinking, growth algorithms, generative fractal geometry or other methods of relating to network structures. Instead, it is about translating a topological description in a topographic description of terrain using digital methods. While there exist many tools for topological landform analysis, design methods for modelling terrain using relations between nodes are still relatively rare. One example are the speculative digital landform models by Beaman [150] where he explores the modification of an existing terrain by the analysis of its morphology, and responding to it dynamically using a catalogue of process typologies. The Wilhemshaven project by Claghorn [68] takes the medial axis of a 2D shape and projects it into 3D using slope angles that depart from the original outline. This method works well, and many variations also exist in architecture, for instance for the production of folded facades.

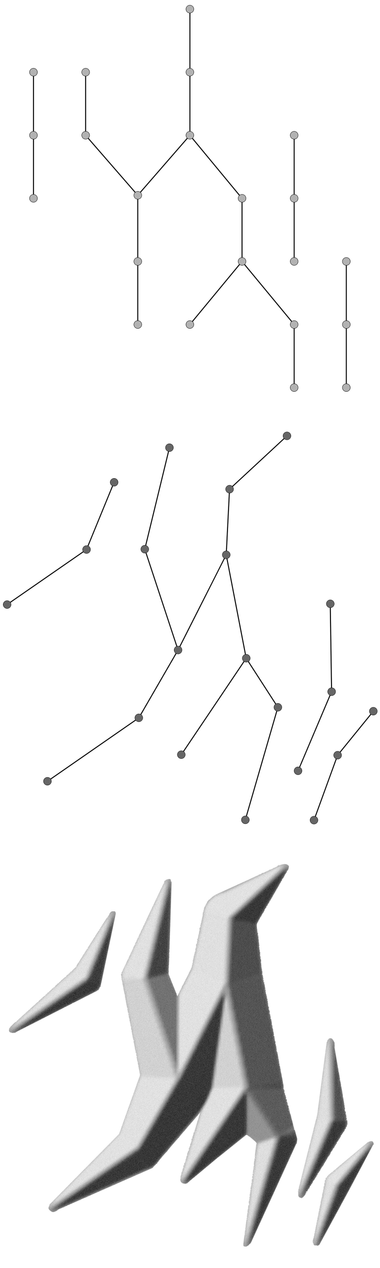


Figure 5.3: Abstract example of the materialisation of a topology into a topography, from top to bottom: A relational network, a network where the nodes are given three-dimensional coordinates in Cartesian space, the same network extended with a triangular primitive shape description from the component Fill In Path from Docofossor with a 2:3 slope ratio.

Topography

Through the application of points, paths, and areas, networks can be encoded in Cartesian coordinate space by using a primitive shape description from Docofossor in Chapter 3 (see Figure 5.3). This is also the moment were an abstract design is embedded in the terrain. The encoding of a topological network can be done using a connectivity graph, however this has not been implemented within this research. Instead, the topology is encoded explicitly using standard modelling techniques like free-form modelling, as parametric relations, or a combination of both. Once the number of vertices and edges are defined, Docofossor provides geometric primitives and parameters for material constraints like the slope angle. Here, the topological network is given position, dimension, orientation. It is therefore able to translate a topological description into topography by elastic deformation of the distance field along the z axis without the need for creating new points nor fusing existing ones. This allows us to design relationships intuitively while maintaining the topology of landform proximities that exist within the digital terrain model.

5.2.3 Forces: Natural and Robotic Processes

As natural processes have always been the formative force in terrain, human intervention over the last centuries often tried to render them statically and predictably in an effort to mediate natural hazards. Earthworks like river embankments, dikes and dams cause a shift to the pre-existing dynamic equilibrium. More recently, under the influence of climate change, we understand how this dynamic equilibrium can shift rapidly in terms of timing and volume in natural hazard events [6]. To give an example, when a river channel is altered using natural hydrological methods, it is able to re-adjust and achieve a new balance in terms of erosion and sedimentation. When this natural process is no longer able to occur; one is faced with either too much erosion or too much deposition, which in both cases may lead to flooding or landslides. While adaptation and modification itself can increase safety as well as the ecological and cultural value, doing so unknowingly is problematic (see 5.4). Moreover, as natural processes continue to evolve over time, static structures in terrain will eventually fail. One possible answer lies in the application of robotics and computation to achieve a better resiliency in terrain. As we have seen in Chapter 4, robotic construction principles enable a dynamic response. Instead of static and pre-conceived, it opens up opportunities for continuous adaptation to an ever-changing condition: a dynamic response to a dynamic system. Looking more closely at the two forces we have just identified, the following Sections will discuss the scope and constraints of natural and robotic processes, making them available for design.

Natural Processes in Terrain

In Section 2.2.2 we have seen that large-scale processes in terrain relate to erosion, transportation and accumulation under the influence gravity, wind and water. On a mathematical level, forces in terrain can be understood by the laws of motion and continuity of matter formulated by Newton and Leibniz [68, p. 250]. Combined, they form a vector field as the sum of all forces acting on a particle. Using computational methods, it becomes possible to simulate large amounts of particle interactions and their evolution over time. Computational methods can be understood as the collection, processing and interacting with information [151]. This information can originate either from physical experiments as described in Chapter 4 or through numerical models. However, simulation comes with its own set of problems relating to the accuracy of the model, the selection of parameters and the non-homogeneous condition of any landscape. This is one of the reasons why physical models still play an important part in the design phase of many water engineering projects. The goal of both physical and virtual models is to come as close as possible within reasonable time-frames, as it is virtually impossible to predict the outcome of a dynamic system over long time periods.

As the scale and time-frames of landscapes go far beyond the possibilities of physical simulation, the design experiments were validated using existing computational tools relating to debris flows. This method enables an understanding of the progressive constraints in the terrain by simulation the flow of natural granular material during hazard events. Apart from the many parameters that go into numeric simulation models of granular material, like friction, viscosity, or entrainments, time and scale play an important role. The resolution of digital elevation models influences the outcome, as well as the expected duration of the event. For any of these tools, a comprehensive understanding of the parameters for specific sites is fundamental to come to valid solutions. Collaboration with experts of the site and the software is therefore essential. When all the physical parameters are set as close as possible to the actual situation on-site, the designer is free to experiment with the form of terrain as this is the last available variable. Depending on the resulting pressure and flow values, different soil textures and profiles can be assembled to prevent erosion and transportation of the terrain.

Robotic Processes in Terrain

In Chapter 4, we have seen that the potential of robotic construction in terrain can be categorised in three concepts: adaptive, emergent, and open-ended. Apart from the natural forces in terrain, robotic processes can be thought of as an additional force, capable of moving material in the opposite direction; uphill. This allows for an entirely new way of working with earthworks. They no longer need to be static, but a continuous adaptation over time becomes a possibility. The in-place deformation of the earth's surface as an adaptive design approach minimises material movement and constrains the design space to a local intelligence, where the underlying form is the starting point of any transformation. As the topography transforms, either by machine manipulation, material interaction or by natural processes, the terrain is analysed, and new instructions are sent to the robotic platform as needed. As such, this construction process does not care much about changing site conditions as it is inherently dynamic in every digging or dumping cycle. At the larger scale, computational methods provide the overall structure, while at the small scale material interactions constrain the shaping of the substance.

5.3 Dynamic Design System

Dynamic equilibrium in terrain will always evolve alongside climatic change. A single simulation is therefore not enough, and the proposed design has to be tested iteratively on minimum, average, and maximum expected material transportation. The output of numerical models depends on the chosen software, but they can be categorised between (1) tools that provide 2D or 3D analytical feedback on paper or in digital form and (2) tools that provide dynamic behaviour [152]. Analytical feedback can be acquired independently from the design environment in external simulation software, where the output gives a graphic representation to be interpreted by the designer. To apply the second category for design, a close connection between the design model and the numerical simulation is mandatory for the information streams to flow back and forth and create an intuitive modelling process. Due to the complexity to bring these methods inside a CAD environment, efforts were made to create smooth interoperability with external software packages. This relates mostly to the use of digital elevation models in the form of regular grids that are used by Docofossor. Here, the DEM can be accessed by both the CAD-environment as well as the simulation tool. As such, the volumetric changes due to the debris flow simulation on the DEM can be visualised and acted upon in the design model.

The procedural and topological approaches to dynamic fabrication can be conceptualised as the movement of shape through a material, where the resulting shape informs the next movement. The procedural approach, directly based on the movement of a bucket, is possible to implement in the design environment but would never come close to the actual result of excavation cycles, as they respond to the local conditions of the site. Instead, a geometric approach on a large scale was conceptualised in the design experiments to be able to talk concretely about formal outcomes. This way, the development of the design scenarios in Section 5.4 are oriented towards form, where the robotic process provides dynamic material movement. It would be interesting to pursue a purely evolutionary model without formal constraints. However, this would entail a computational implementation of Docofossor without the limitations of the current parametric environment (see also Section 6.2.2).

5.3.1 Constraints in Digital Design and Fabrication

The design constraints, given by the material and the machine, are described in Chapter 4 as substance and grammar respectively. While the substance determines aspects like slope angles and mechanical properties, the robotic earthmoving grammar determines all the ways it can be excavated, transported and deposited which is closely related to the actual machines on site. Together with the natural processes in the terrain, they make up the constraints relating to the processes of making. The fourth category, described above as *form*, complete the constraints based on the landscape architectural function and design intention. The procedural and topological approaches to earth-moving from Chapter 4 are translated into a dynamic design system for the larger landscape scales in the following Sections. The constraints description below is not meant to be exhaustive but a beginning towards a computational design system for dynamic formation in terrain.

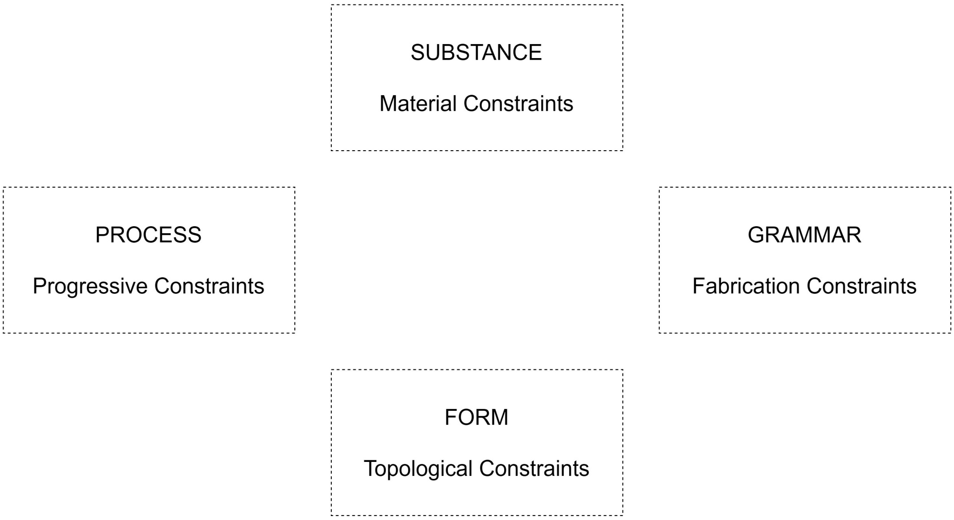


Figure 5.4: Four core concepts and their related constraints for dynamic earth-moving.

- *Material constraints*: As we have seen in Section 4.2.3, the substance of terrain determines the possible shapes it can take. Particle size, angular or round particles, and degree of saturation all influence the natural formation of this granular material. The build-up of material layers, its texture and density, has a significant influence on how it performs at its surface. Because of this, the formal expression of a landscape does not only reflect the immediate material on its surface, but includes the expression of the subsoil and sub-grade on which it rests. The underlying form is therefore not only a formal question but a material question as well. The easiest way to notice this intrinsic dimension of the terrain is by vegetation growth. Wetness, dryness, friability, and slope cohesion informs one on the material conditions beyond its surface [2]. The material constraints relate to repose angles, soil textures, soil consolidation, and soil profiles. These parameters can be encoded in Docofossor though rules of thumb or accessed via simulating using computational methods. These can be determined in advance using the soil texture, or dynamically acquired during excavation using force feedback or other remote sensing techniques.

- *Progressive constraints*: Section 5.2.3 describes the natural processes acting on terrain in relating to their evolution over time. Because these processes evolve continuously, design methods have to iterate to come to valid results. Instead of determining a single outcome, the design model is updated over time to reflect the changing conditions. Through computational methods, an understanding of the material transportation over time is simulated, which in turn re-evaluates the design and re-frames the objectives. Design strategies have to allow for a range of possible scenarios that can only be materialised in the future. By modelling terrain using parametric or computational methods, the design can automatically adjust to the new site conditions without human intervention. This can be achieved by updating the terrain map regularly, combined with relational modelling methods that change the designed topology accordingly. The precision of the simulation software and unforeseen climatic change play a role in the design scenarios. Making future design adjustments seems unavoidable. Therefore, maintenance plays a vital role in the progression of the landscape.

- *Fabrication constraints*: Section 4.2.4 describes the constraints relating to the mechanical movement of granular material. They relate to both the shape of the tool (end-effector) and the motions with which it can be moved in space (robotic platform). They directly relate to the possible shaping of terrain by limitations in planning and reach of the chosen equipment. Not all parameters have to be encoded in the design description itself as the robotic platform can command many of the movement and iteration. However, path planning and sequencing of the excavation has to be taken into account, especially relating to the material re-distribution as the robotic platform might have to move over newly deposited material. This can be achieved by iterating over interim construction goals. The fabrication constraints have not played a significant role in the design experiments as the robotic platform that formed the basis for the designs was still in development. However, the free-form prototype build with HEAP (see Section 4.4) shows how path planning and reach are encoded in the final design description.

- *Topological constraints*: Section 5.2.2 describes how formal constraints are encoded using topological rules. By applying the relative and absolute modelling methods of Docofossor, static and dynamic descriptions of a design are achieved. Here, all the local site conditions are taken into account. These range from roads to water tables or other features that should not be disturbed in the evolutionary design scenarios over time. It also includes the formal intention of the designer by defining the overall shape and surface relations using design lines. Thus, the topological constraints exclude all areas that should be left untouched, reconnects surrounding areas to any topographic change, and includes the designer's intention on shape and structure. The design is therefore not a final static geometric description, but is defined by controlling a range of possibilities as a topological description for terrain.

5.3.2 Design Process

The four concepts substance, process, grammar, and form can be encoded in parameters to make them available for design as material constraints, progressive constraints, fabrication constraints and topological constraints. This involves three phases: preparation, design and execution. The preparation phase covers the data collection and defines all the variables used in the dynamic design model. The design and execution phases rely on iteration to enable dynamic change over time. While the execution phase uses physical manipulation, which is subsequently scanned and interpreted, the design phase leans heavily on computation for a dynamic response. In both cases, the DTM provides the relation that is established between the survey, modelling and manipulation/simulation methods as described in Chapter 3 and 4. This integrated design model is therefore central to the process of design and the process of physical manipulation [142]. Figure 5.5 shows a high-level overview of the design process workflow.

Preparation Phase

The preparation involves the sourcing of topographic data, material parameters, identification of natural processes, selection of the robotic platform and site context concerns. The material constraints parameters are used throughout the modelling setup. They determine the slope angle for cut and fill as well as the material cubature available for design. In the simulation of material transport, they are used to determine erosion and friction values. The fabrication constraints determine the possible shape creating using a specific digging and dumping cycle. Design scenarios for the terrain's evolution are set using progressive constraints by interim goals. This is also the moment where simulation software will be selected to gain insight into the natural processes acting on site. Finally, the topological constraints come from a site analysis and define the design space. A careful composition of the parametric or computational model is essential as this determines for a large extend the flexibility in modelling design solutions. Once a dynamic digital model is set up, the design process can start.

Design Phase

The design phase tests design ideas by iterating over natural and robotic processes acting on-site over time. As such, the reflective design loop between framing, forming and finding is made possible by surveying, modelling and simulation techniques on the digital terrain model. The survey, in this case, is not a physical topographic survey but rather a digital analysis of the DTM that, in turn, provides the parameters and sets the objectives for the modelling process.

- *Framing:* At the start of the design phase, objectives are set for the first iteration. The time-frame of a single iteration is dependent on many factors and can cover anything from a single day up to years. As the underlying form of the terrain determines for a large extent the design space, it is analysed on landscape elements like watercourses and static artefacts. This is also the moment where existing landforms are determined using properties of slope angle, orientation and curvature. These additional information layers can then start to inform the operations in the modelling stage. In subsequent iterations, a new DTM that originates from the modelling and simulation stage is analysed instead of the original terrain, forming the basis of the next design loop.
- *Forming:* The topological relations are set up using design lines, either parametrically or algorithmically, to stay as flexible as possible in the subsequent modelling iterations. While it would be good to clearly understand which topological relations need to be dynamic, it is almost inevitable that this setup needs to be adjusted when more insight is gained throughout design process. Though this can be a tedious task at the beginning, it enables fast and flexible testing of variations in the final stages of the design process. The design lines operate on the DTM using either relative or absolute operations in Docofossor. Now, the model is encoded as a topography that can be visualised as well, using the original point cloud as a constant background for interpretation. The modification of the DTM in subsequent iterations is straightforward if the model is set up correctly, as it only involves the adjustment of parameters like slope angles or cubature. The modelling operations do not enable a procedural approach that mimics robotic behaviour because they will never be the same as in physical construction due to their dynamic processes. Instead, a topological approach was used for the design experiments (see Section 5.4).
- *Finding:* Once a design solution needs to be validated on its performance to understand the formal outcome of natural processes, computational tools can use the same DTM to simulate hydrological or mass movements. As the implicit modelling tools of Docofossor operate directly on the raster grid, establishing the connection to these software packages is quite simple as they

generally operate on grids as well. The parameters used for the simulation should be in tune with the chosen time-frame for a single iteration, so that the expected erosion, transportation and sedimentation of material match together. Once the simulation has been executed, the resulting topographic change is embedded in the DTM to form a new starting point for the next iteration. This cycle continues until the design evolution is well understood.

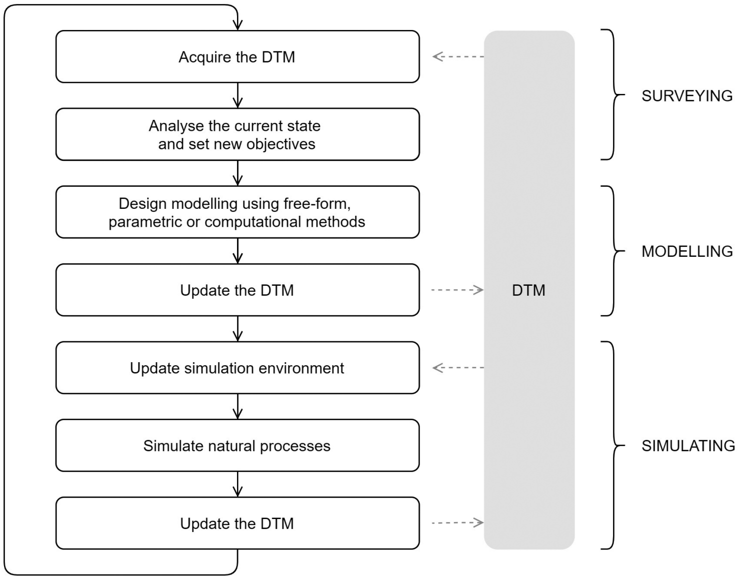


Figure 5.5: Flowchart of a single iteration during the design process, iterating over surveying, modelling, and simulation methods.

Execution Phase

The execution phase starts by connecting the design model to the robotic execution platform. By comparing the found geometry during construction with the desired geometry, real-time adjustments can be made based on found material properties, available cubature or changes due to unforeseen events. This process can be automated to ever-increasing levels of autonomy and allows for dynamic design strategies that evolve over time. Section 4.4 described the necessary hardware and software solutions that were developed within the scope of this research.

5.3.3 Design Techniques

The design techniques and tools described in the previous chapters form the basis for a dynamic design approach. By iteratively designing and testing proposals, dynamic formation scenarios can be investigated. They are conceived between two forces in terrain: natural and robotic processes. While the robotic processes are conceptually understood and tested in small scale formation experiments, the large-scale designs leverage computation to simulate evolutionary concepts. In each iteration, the topography is surveyed, modelled and simulated. Below follows a description of the tools used to establish a dynamic design approach in the design experiments that are described in Section 5.4.

Surveying

Surveying methods inform the dynamic modelling approach, where each iteration is analysed anew as the topography evolves due to the simulations that went before (see Figure 5.7a). Here, *surveying* does not relate to terrain triangulation in the landscape but to a survey of the digital terrain model. By comparing the DTM from the previous step to the current state, continuous cubature observation is made possible. This gives insight into how much, and where, erosion and deposition takes place. From here, new constraints parameters can be set in response to the analysis. Apart from these quantifiable variables, the result is also qualified on landscape architectural intentions, which are translated to the DTM through topological constraints. The same can be said for the material and fabrication constraints. While these step can be automated to various degrees, in the design experiments procedures were mostly executed manually.

Modelling

The modelling tools used for the dynamic design techniques are described in Chapter 3. They consist of relative and absolute modelling operations using distance functions in a DTM. Figure 5.7b shows an example of a topological network. Starting from a base DTM, points, lines and areas define a new structure that correspond to ridges and valleys of a new topographic prototype. Here, a differentiation is made to lines that are position-critical, e.g. that align to roads or other existing artefacts that should not change, and those that can be altered during the design process. These are subsequently defined parametrically to enable fast and iterative modelling. A primitive shape description is then applied to this network using one of the operations from Docofossor. By adjusting the width, height, and slope parameters, the primitive shape is given a dimension corresponding to the specific site. This topography is visible in Figure 5.7c.

Simulation

The techniques relating to the simulation of natural processes rely on the operability of Docofossor's data structure. Once a design is ready for testing, it is sent to the simulation environment using the ASCII Raster file format. For the rapid mass movement simulations, the debris flow module of the RAMMS software package from the Swiss Federal Institute for Forest Snow and Landscape Research (WSL) was used. The simulation software handles all the soil friction parameters to accurately predict erosion, transport and sedimentation of debris flows, which were set in close collaboration with Brian McArdell from the WSL. Figure 5.7d shows the result of a simulation as the final flow depth. The amount of erosion and deposition is then respectively subtracted and added to the DTM to incorporate the natural processes in the design model. Apart from erosion and deposition, the software also outputs pressure and velocity. These values give insight to areas where the topography might be too steep, or areas that need a different material texture able to resist erosion.

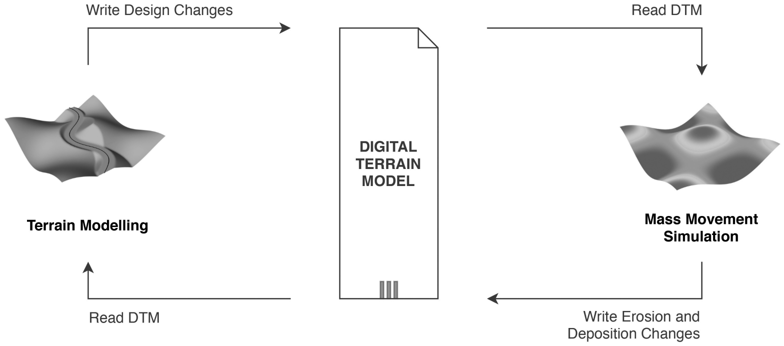
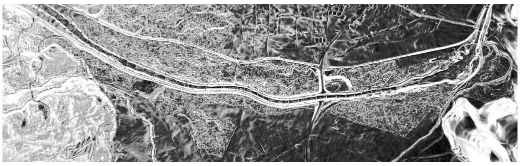
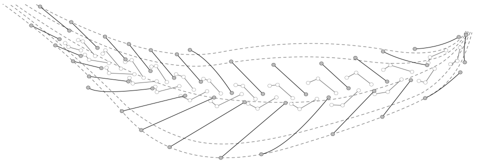


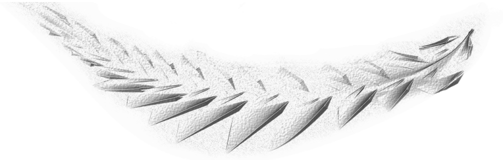
Figure 5.6: Data flow between modelling and simulation, where the DMT is iteratively changed in the respective environments (the survey is excluded here, as it happens in the modelling environment as well).



(a) Terrain analysis

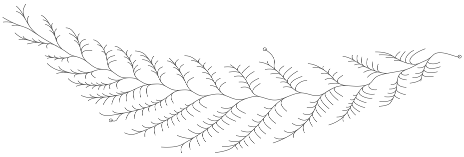


(b) Topological model



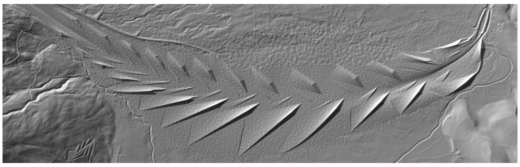
(c) Topographic model

(d) Simulation



(e) Robotic agency

(f) Material balance



(g) Design in T+20 years

Figure 5.7: Selection of design techniques by Students Caspar Trueb and Lorin Wiedemeier.

5.4 Experiments in Dynamic Design

To explore the potential of robotic earth-moving for landscape architecture, three design studios were held within the scope of this research as a collaboration between the Chair of Christophe Girot and Gramazio Kohler Research. The three design experiments were not defined in advance of this research. Instead, ongoing insights during the experiments re-framed the object and context of the following studios. All the experiments included a physical component that is described in Chapter 4, which informed and structured the robotic principles applied in the design. Based on these procedural logics and the feedback mechanisms, the following Sections will discuss the results of dynamic construction at a larger scale by looking at the three dynamic design components; framing, forming, and finding.

The design techniques explored in the experiments formed the basis of the dynamic design system that is elaborated in Section 5.3. From the first studio, it was clear that a better terrain modelling tool was necessary in order to model the terrain more effectively and dynamically. This has led to the development of Docofossor (see Section 3.4), as well as implementing numerical simulation which was subsequently applied in the second and third design studios.

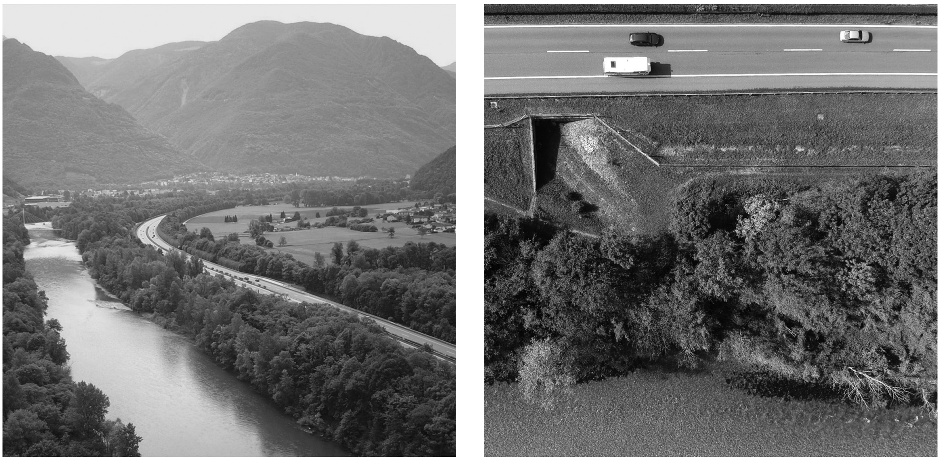
5.4.1 Varying Object and Context

The design experiments were not defined in advance of the whole research but followed the principles of reflective design, where each experiment was evaluated in order to re-frame the object and context of the next. As such, the formulation and tools of the experiments increased in precision and usability. As each experiment resulted in around ten different projects, only a few examples can be highlighted in the following sections. However, they are chosen to represent the most important outcomes of the experiments in relation to dynamic design strategies for robotic landscape fabrication. The work was validated using simulation and by qualitative review of an international expert panel.

5.4.2 Design Experiment 1: Adaptive Transformation

Object and Context: Sound Barrier in the Riviera Valley, Ticino

The first design experiment took place on the Riviera Valley, where the Ticino River deposits sediments for over thousands of years. Up to the river correction between 1888 and 1912, the area was a vast marshland. By studying the history of the valley, one becomes aware of the constant change and ever-increasing complexity of this artefact. The valley is like a palimpsest, a superimposition of natural, agricultural, and urban networks changing over time. The A2 highway, constructed in the 1960s is the main connector but at the same time main border and noise emitter in the valley. The Ticino river correction, together with the highway, form the main infrastructural works on the valley floor (see also Figure 5.8).



(a) Overview of the Valle Riviera (b) Orthophoto showing the depth of the site

Figure 5.8: Riviera Valley in Ticino and the small stretch of land between the A2 Highway and the Ticino River.

Objective and Methodology

Due to the high noise levels from the highway, the design focussed on building an earthwork that is able to shield the adjacent villages as well as function as a new leisure area with bike paths and small park facilities. The stretch of land is situated between the highway and the river, forming a linear landscape structure of 20 to 150 meters wide and 5 kilometres long. Using adaptive strategies, loose and granular material was to be transformed into a functional sound barrier. Instead of extruding a single barrier profile along the highway, intricate sound absorbing and reflecting topographies had to be explored, under the recognition that constructing complex geometries takes roughly the same effort as constructing planar surfaces in robotic fabrication. This also promoted the inclusion of circulation and water drainage swales within a single terrain structure.

During this first design experiment, digital modelling techniques were based on methods in free-from modelling and parametric design using BReps. The robotic mechanism in the small scale experiments described in Section 4.3.2 formed the inspiration for large-scale transformations, that were subsequently modelled in 3D. Various parameters were set in advance. For example, one parameter de-

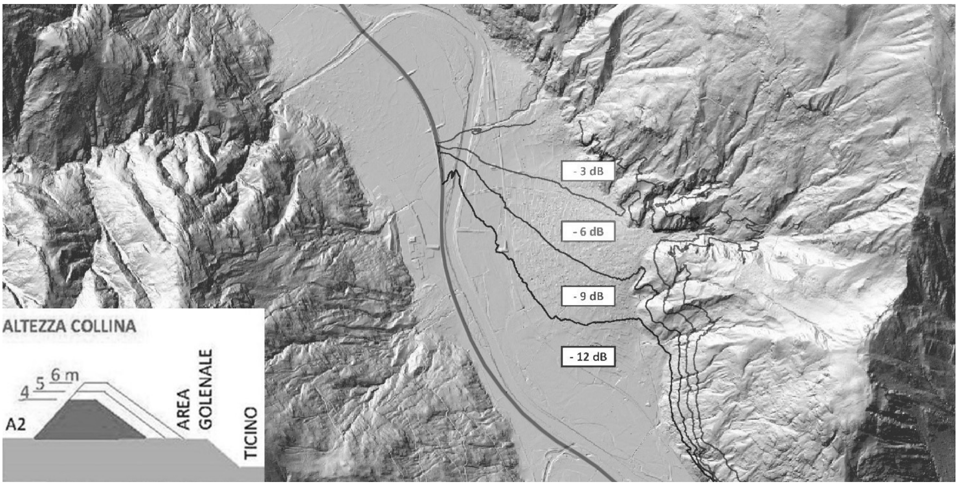


Figure 5.9: Sound study on noise reduction using a earthen landform (source unknown).

fined a path that takes a person from point A to point B with a maximum slope of 6%. Using the point cloud model of the whole valley as a 3D base, robotic operations were limited to the spreading and compression cycle, which promoted highly local transformations while balancing cut and fill.

Framing

During the site visit, different soil samples were taken and brought back to the studio. Sieves were used to separate the larger particles and subsequently settle the fine particles in water, which enabled the determination of the soil texture by measuring their volumes. As the site was directly aligned with the river, most samples were either categorized as loamy sand or sandy loam. With such low clay and silt content, it meant that the maximum slope angle achievable on-site was not more than 33.7 degrees (2:3).

For the sound performance of the barrier, Kurt Heutschi of the Acoustics lab of the Swiss Federal Laboratories for Materials Science and Technology (EMPA) provided the necessary expertise. The resulting geometries that were modelled for the absorption, spreading, and screening of sound coming from the highway were not tested computationally but validated by expert review. Rules of thumb in distance and height of the barrier were applied to reduce the spread of the highway noise in the valley. These relate mostly to the upwards or downwards bending of sound waves away from directs line of sight by varying atmospheric conditions. Because of the steep mountains along the valley floor, particular interest was taken in reducing the so-called ground effects for the sound attenuation. This enabled not only the creation of rather low barriers, but provided design opportunities for surface patterning and textures.

The robotic strategies explored in the physical experiments are summarized in Section 4.3 as two new formation concepts: local transformation and geometry by iteration. This robotic agency meant that the final topography was defined not only by a top-down shape description, but by local differences in terrain as well. When more material was available, the sound barrier could grow higher. This relates to the material depth both in horizontal and vertical dimensions. Where possible, the river was widened to minimize erosion which also made this material available for the barrier. As such, there was an inherent relation between the current form of the terrain and the newly created structure. The final expression of the topographic structure resulted from the individual spreading or compaction cycles as explored in the small scale experiments using the robotic mechanism.

Forming

By utilising the border of the highway and the bank of the river as design lines, material shifts were orchestrated in perpendicular fashion so that a single cross-section would always maintain the material volume balance. Here, the distance to the highway determines the height of the barrier in order to maintain the necessary screening effect (see Figure 5.11). This also enabled the barrier to exist as multiple hills or dikes, enabling circulation and water flow throughout the area (see Figure 5.11.

Instead of modelling every spreading or compression cycle in the digital terrain model, a robotic construction plan was made to inform the design principles. This was done out of necessity as it is virtually impossible to interpret computer code formally, and because Docofossor was not yet developed. Irrespective of how the landscape structure would actually be build using procedural processes, it created a link between the physical reality of the site and the new landscape structure. Figure 5.10 shows how an autonomous excavator would shift material over the terrain, starting by stripping material, pushing it along and finally spreading and compacting it into a new structure. The implementation in the digital terrain model of the site is shown in Figure 5.12, where the cubature is calculated and balanced throughout every linear operation.

Finding

As the first design experiment did not rely on simulation, the design process did not involve a reflexive design process but followed a more traditional model in reflective methods void of computation or simulation.

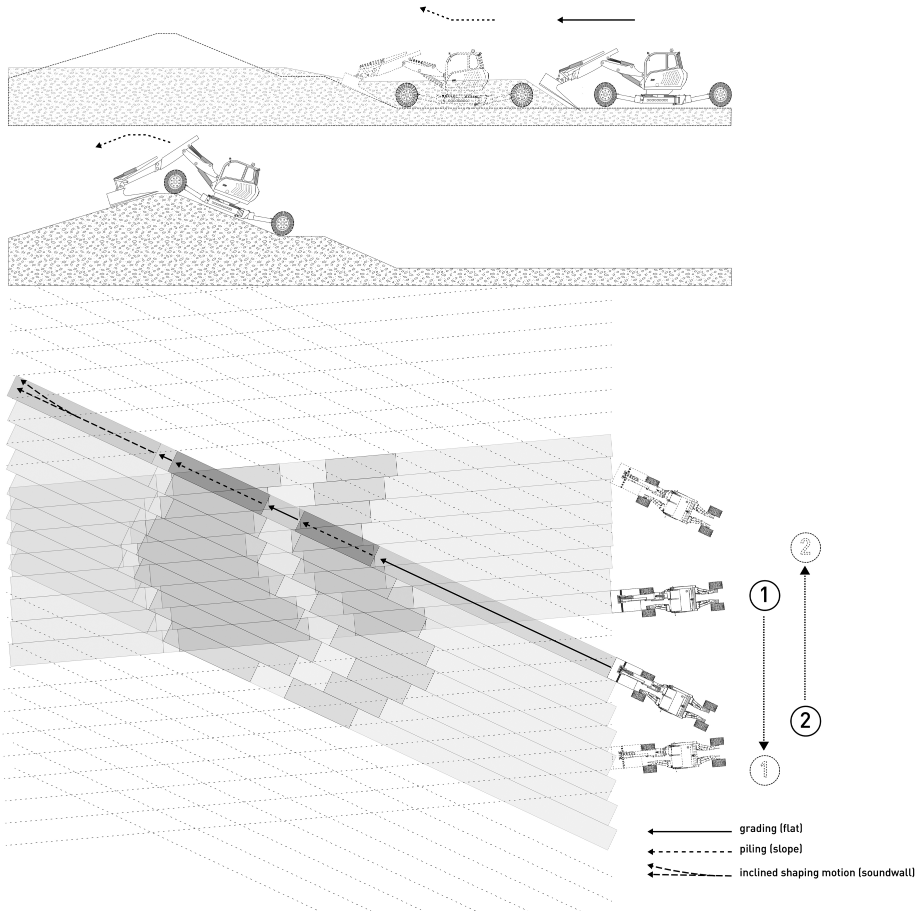
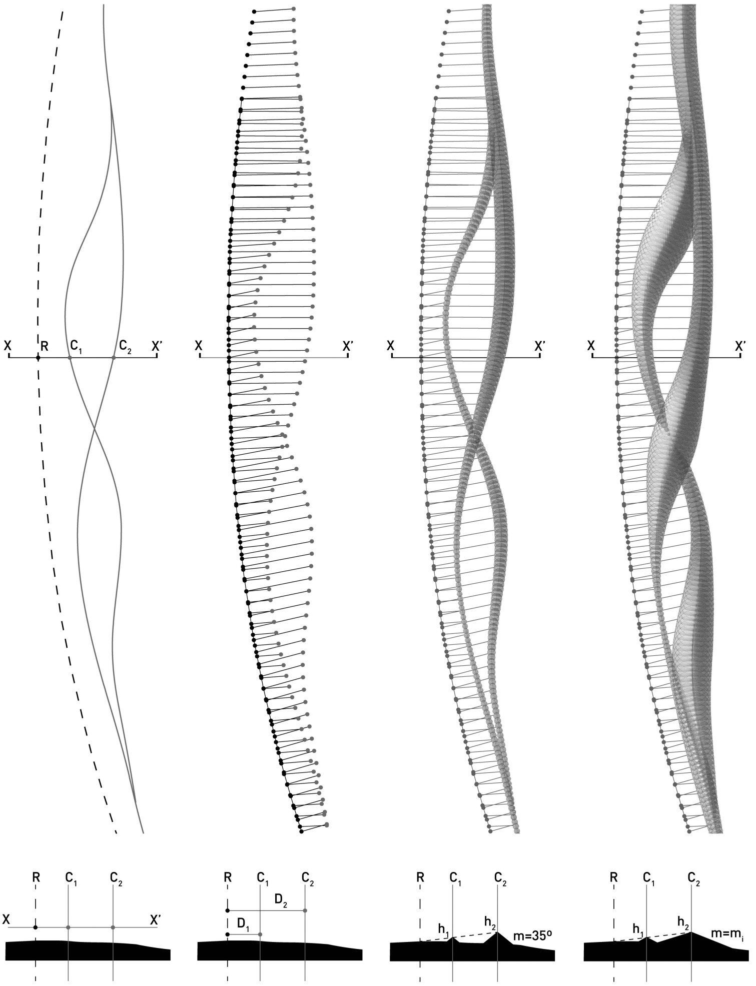


Figure 5.10: Robotic construction principles. The top section shows the redistribution of the local material into a new structure. The bottom shows the same in plan view, including direction and overlap. By students Ladina Ramming and Thorben Westerhuys.



Existing Terrain $n(C)=700$

Distance ∝ Height $D_i = R_i - C_i$

Fixed Slope $| m=35^\circ | h_i \propto D_i |$

Varied Slope $| m=m_i | h_i \propto D_i |$

Figure 5.11: Topological model in plan and section of the sound barrier. The distance to the highway and its orientation determines the variable slope of the barrier. By students Abraham David Noah and Bing Yang.

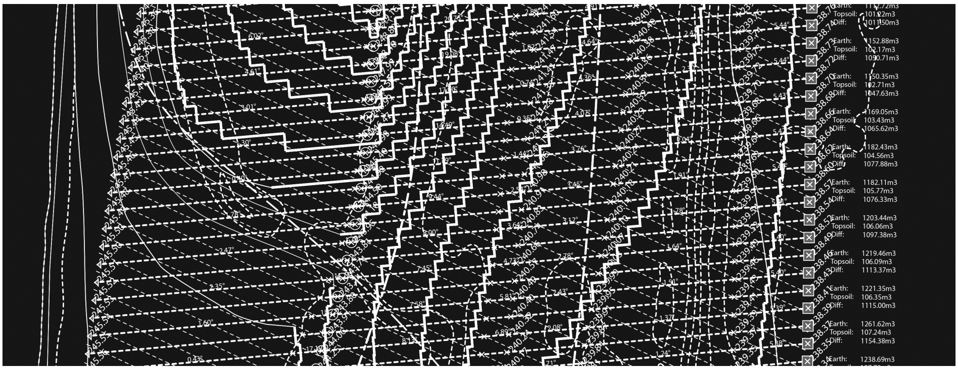


Figure 5.12: Code made visible (detail). The robotic movements are translated to paths showing the cut and fill balance in topsoil and subsoil. By students Ladina Ramming and Thorben Westerhuys.

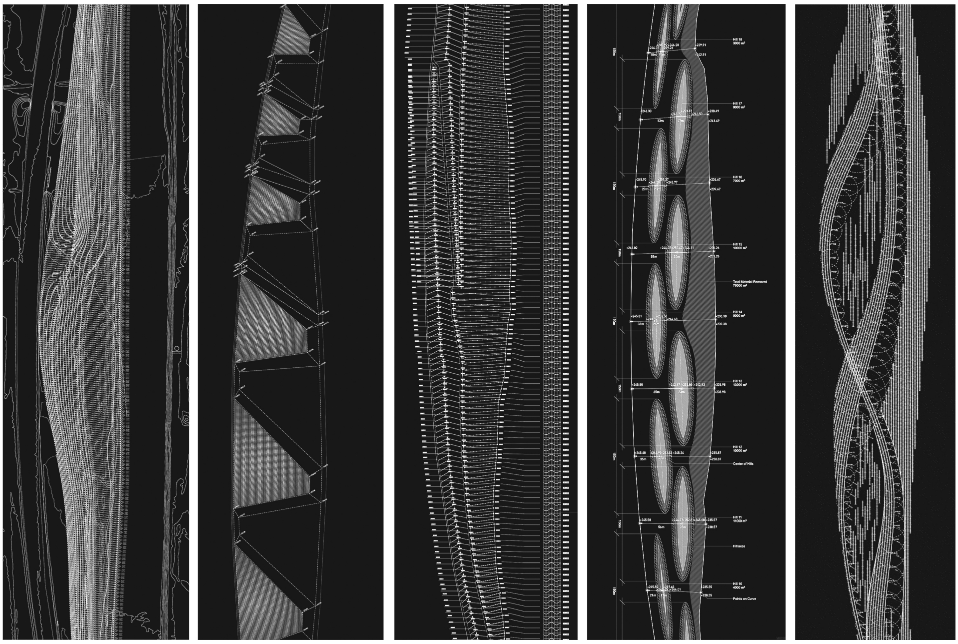


Figure 5.13: Code made visible (overview). The movement of the robotic platform displayed in plan view for five different designs. By students David Abraham, Alessandro Canonica, Kenichiro Endo, Gabriel Fiette, Milan Jarrell, Marius Oneta, Ladina Ramming, Anna Rickli, Thorben Westerhuys, and Bing Yang.

Results

The application of adaptive transformation strategies resulted in minimal material movement within the site while creating a new performative landscape structure. The robotic agency in this experiment was understood to shape the terrain depending on the found material adaptively. As such, the designs responded procedurally to the slope of the valley, the riverbed, and the highway establishing a continuous landscape topology that functioned as a sound barrier but also enabled leisure activities to take place. Starting from the material constraints, a new robotic process was introduced in the valley. This process was translated to the site by applying cut and fill operations relative to the terrain using various topological rules relating to the new structure. This resulted in an adaptive transformation that was dependent on the underlying form of the terrain. The intent and structure of the design was presented as a robotic construction plan without modelling the topography or formal expression directly in a digital model. While this provided a different understanding of the topology, it was still hard to read without lots of interpretation and imagination by the reviewer. As the scale of the geometric formations related mostly to single spreading and compression of an excavator bucket, it does not translate well to large-scale landscapes, and it is likely that these small patterns and textures would erode quickly. By spreading and compressing material locally, an informed material transformation rendered this terrain vague[1] between the river and the highway into a site-specific structure and performative surface for the whole valley.

5.4.3 Design Experiment 2: Emergent Transformation

Object and Context: Debris Flow Remediation in the Bondasca Valley, Grisons

The second design experiment was located in Bondo, Grisons, where since 2011 a chain of major tectonic events deeply affected Val Bondasca requiring urgent remedial measures. In August of 2017 the Piz Cengalo collapsed and over three million cubic meters of rock created one of the largest landslides in Swiss memory. A wall of mud and boulders flowed towards the village of Bondo following the course of the existing Bondasca River, obstructing the main road, washing away houses and causing human casualty in the upper valley. As there still remains 1.5 million cubic meters of rock in an unstable condition still threatening the Bondasca Valley, more debris flow events are expected in the years ahead triggered by heavy rain or by the melting of permafrost due to effects of climate change.

---

[1] The term *terrain vague* adopted by Ignasi de Solá-Morales designates a condition where the uncontrolled growth superimposition of urban and landscape infrastructure has led to a deteriorated, fragmented geographical context [153].

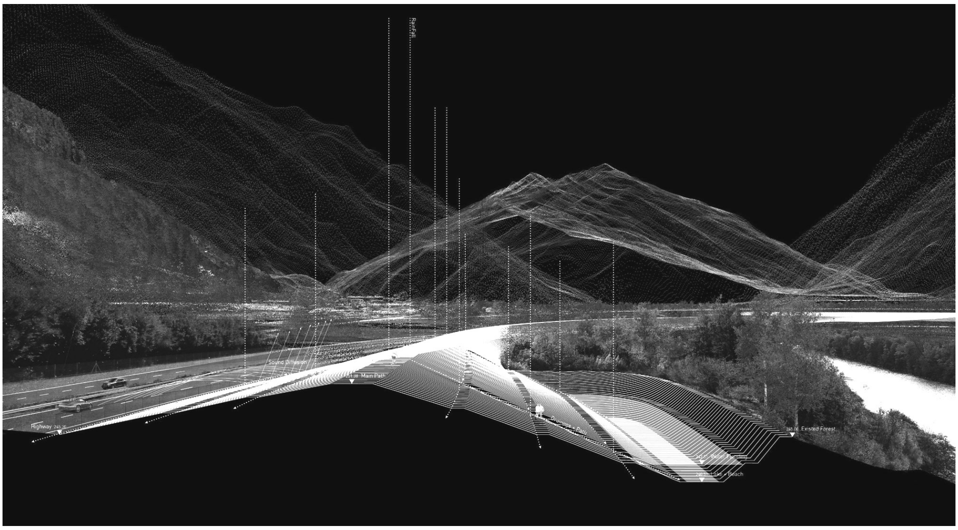
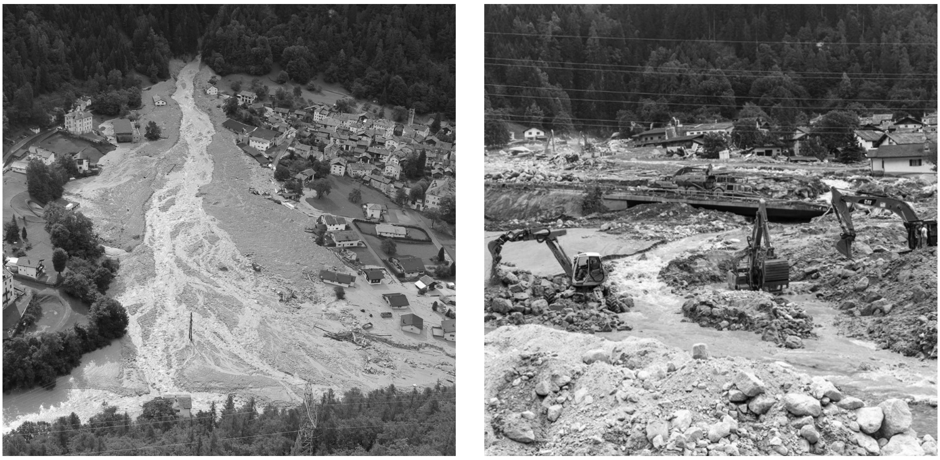


Figure 5.14: Section-perspective, showing the new landform embedded in the larger point cloud model of the Riviera Valley. By students Maximilien Durel, Shohei Kunisawa, and Nicolas Wild.



(a) Overview of the event on 21.08.2017.

(b) Heavy equipment at work on 23.08.2017.

Figure 5.15: The debris flow arriving in Bondo on August 2017, overflowing from it's banks and catchment basin into the village Bondo. Source Centro Giocometti (a) and Rolf Canal (b).

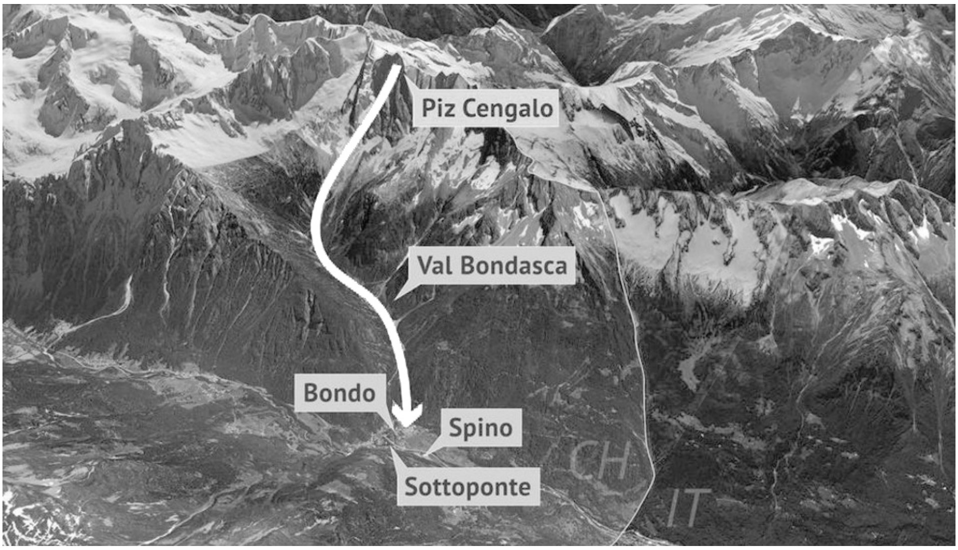


Figure 5.16: The pathway of the debris flow after the collapse of the Piz Cengola. Source Somedia Press AG.

Objective and Methodology

In response to the first dynamic design experiment, where the scale of the robotic operations did not translate well to large-scale landscape construction, a more abstract robotic process was chosen for the small scale experiments in the sandbox (see Section 4.3.3). The translation of these conceptual experiments in formal and procedural properties to large-scale terrains benefitted from the development of Docofossor, which at this point in the research was developed far enough to be implemented. This enabled a topological modelling approach using implicit operations on terrain.

Where a typical engineering solution for debris flows would create a large detention basin to hold the material coming down from the mountain, the studio questioned this approach as it had already failed during the first large event in 2017. Instead, this design experiment explores solutions where the material from the debris flows would gradually be re-distributed to take a performative shape along the river course and its banks. This method was implemented retrospectively with a starting point before the 2017 event. Using only sand, gravel and rock from the landslide, robotic design principles and dynamic design solutions were to mediate further risks and on-site disruptions. By re-imagining the making of terrain in an alpine setting, new potential for reconciliation between natural processes and designed environments were sought. Based on dynamic modelling principles, the experiments are to establish a procedural and iterative design approach using three time-frames (see Figure 5.17). Due to the continuing hazard events on-site, each step was to be validated by mass movement simulation on safety and material balance.

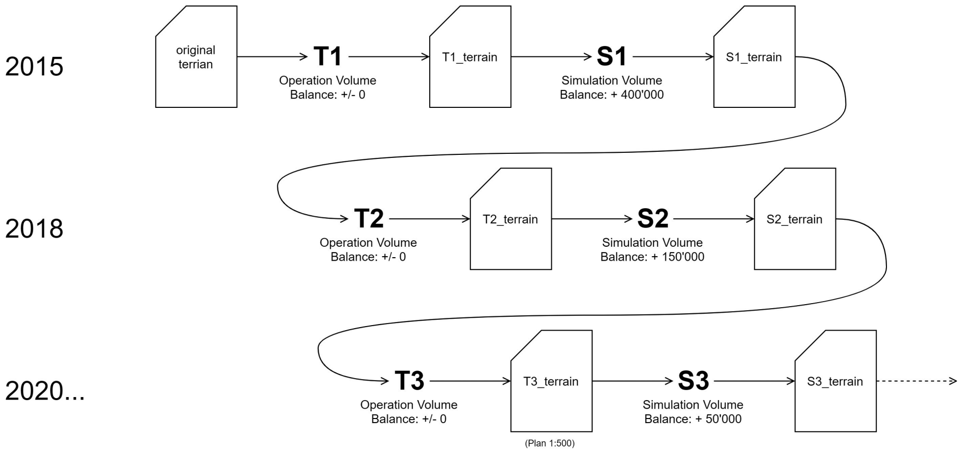


Figure 5.17: Evolution of the design phases: T1, T2, and T3 represent the topographic intervention, while S1, S2, and S3 represent the debris flow events that are simulated in the digital terrain models.

Framing

In consideration of the material make-up of the debris flow, the studio selected three main grain sizes for the construction of new terrain. They consisted of sand and gravel, cobbles and rocks, and boulders. This was done for both the robotic formation experiments using the dumping cycle in the sandboxes as well as for large-scale design. This resulted in new soil profiles where large boulders are able to prevent erosion on exposed banks. While the soil texture varied from very fine particles to boulders weighing up to 5 tons, the soil horizon was rather uniform as all material consisted of the same broken rock material.

The debris flow affecting the Bondo village consisted of a mixture of broken rock and earth and water that was accumulated along the Bondasca Valley. The interaction between fluids and sediments create a seemingly liquid substance where the bigger boulders form the head of the debris flow, and the rocks are suspended in finer particles (see Figure 5.19). The main impact of this flow is determined by its large mass, an almost unstoppable force when running over steep terrain. Beyond the danger of spilling over banks of the existing Bondasca river, debris flows can grow in size by scoring the bed and entraining this material. Existing countermeasures mostly rely on concrete or steel structures that consolidate sediment or bed torrents, prevent slope failures, erosion measures using check dams or walls or structures that dewater or trap the debris flow. In the absence of any of these

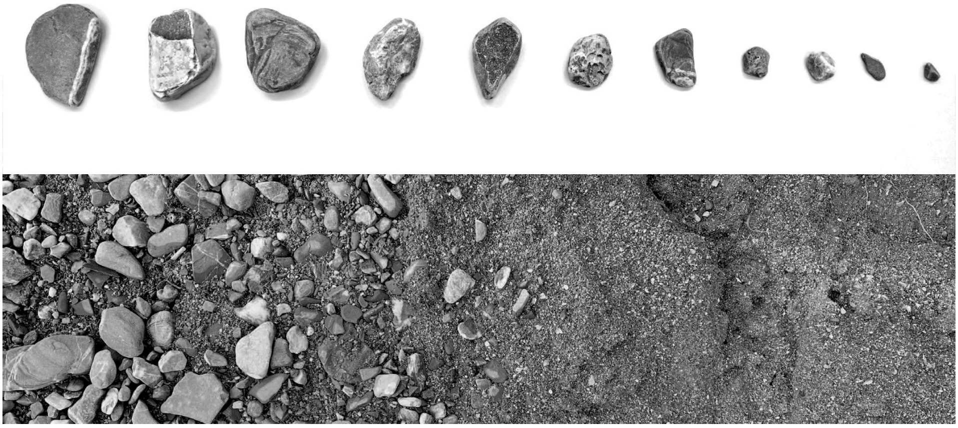


Figure 5.18: Selection of gravel found on the banks of the Bondasca River. The experiments took sand, gravel and boulders into account for the material build-up. By Students Elizabeth Levy and Stanislaw Modrzyk.

measures that will inevitably fail over time, a soft approach was investigated that would emerge out of robotic processes.

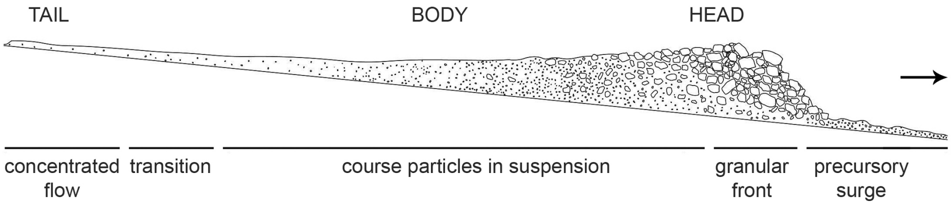


Figure 5.19: The differentiation in head, body and tail of a debris flow running downhill. Redrawn from Brian McArdell.

The robotic agency consisted of the strategies that were explored in the physical experiments. Here, material interaction, dynamic aggregation and landform integration were investigated to dynamically grow the existing terrain using the material deposited by the debris flow. After each event, the new material was displaced and deposited into a new structure to store and catch future deposits. This step is crucial as the natural termination of the debris flow would block the channel and material would overflow into the village. Hence, human intervention is necessary to maintain the village in its current place. Unstructured forms in terrain that resulted from the debris flows informed the next material distribution by analysing the material build-up over time. These processes of material and machine computation form an emergent behaviour that establishes a new dynamic equilibrium.

The creation of a new equilibrium between natural and robotic forces can be achieved by simulating the topography in every step. Strategic material aggregation is therefore capable of directing the flow away from the village in every iteration in time. Figure 5.20 shows a site-specific design intention. Here, the transformation of topographic form starts from the existing terrain, landscape elements, and artefacts. These can now be translated to topological parameters to determine the minimum and maximum allowable design space in Figure 5.21. This description relates to performative as well as landscape architectural aspects.

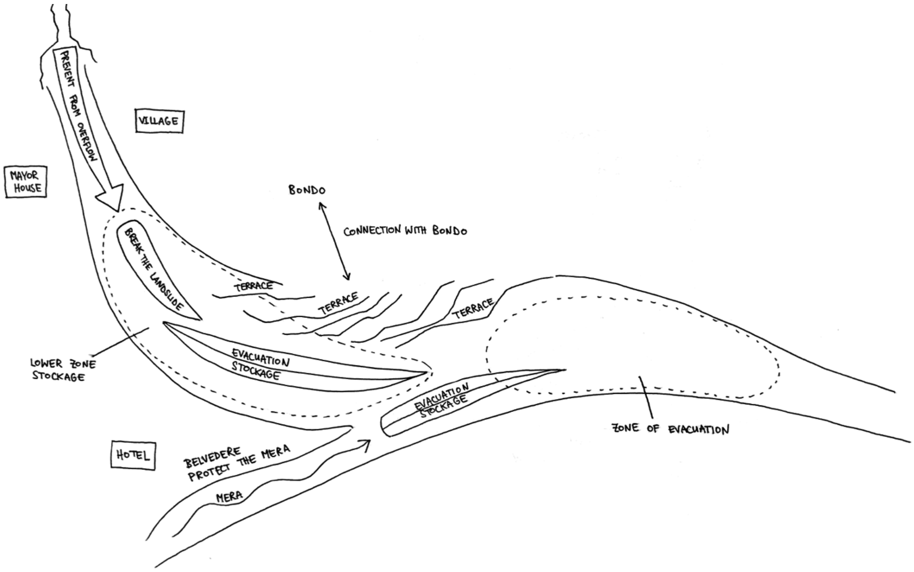
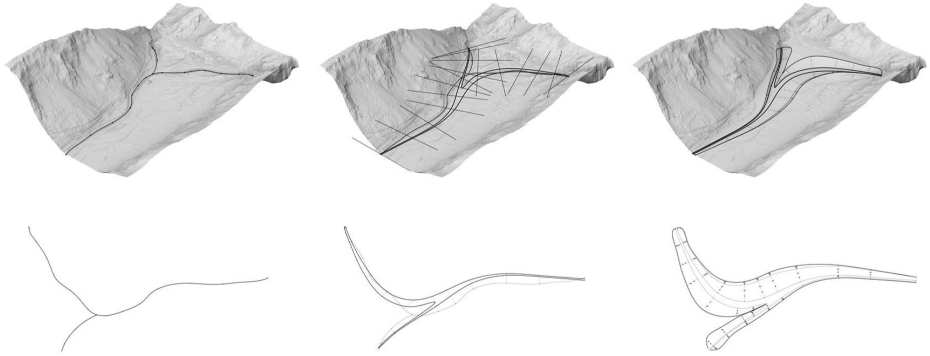


Figure 5.20: Site specific description of Bondo in topological intentions, by students Kelly Meng and Dawit Tadesse.

Forming

Following up from *framing*, the dynamic design system enables the modelling of both natural and robotic transformations in the digital terrain model. The parametric modelling of the topological constraints enables the adjustment of dimension variables between every simulation. This is made possible by the implicit modelling methods of Docofossor, where the *shape* relates to the material constraints and the *motion* to the new terrain structure (see also Section 3.4.1).

The topological design intention from Figure 5.20 is translated into a parametric and topological model as highlighted in Figure 5.21. At first, a skeleton of points and lines trace the underlying form of the terrain as defined by the erosion in the terrain due to the Bondasca River (Figure 5.21a). After this step, this design curve is adjusted to a new terrain structure and given more space to receive and redirect the debris flow. (Figure 5.21b). The final step takes the design curves and creates a three-dimensional skeleton that includes all the new embankments tracing the new channel back to the existing terrain (Figure 5.21c). At this point, the new structural skeleton is completely defined parametrically by the underlying terrain based on the existing river bed. From here, this topological model is transformed into a topographic surface as visible in Figure 5.22. All the cut and fill operations are parametrically defined using Docofossor to render a new landscape structure. Of course, this topological model was designed using many iterations between framing, forming and simulating the debris flow to adjusting each variable in this model.



(a) Underlying structure (b) Design curves (c) New structure

Figure 5.21: Digital modelling of the topological constraints. (a) First variables: setting the underlying form based on control points of a new design curve. (b) Second and third variables: displacements of the design curves and definition of the new river area. (c) Variables four and five: include all topological relations and distances of the new embankment structures. By students Kelly Meng and Dawit Tadesse.

The construction of the topological model is essential to accurately guide the transformation of the digital terrain model in response to the robotic strategy. In general, it consists of an overall skeleton that holds all the constraints coming from the site. Zooming in, this is accompanied by smaller structures that relate more directly to emergent processes. By implementing relative operations, these structures can grow iteratively by increasing the fill-parameters. This way, the model corresponds to the actual material balance coming from the simulations. The translation of a robotic process on site is visible in Figure 5.23, where the amount of cut and fill is annotated on a plan. Here, amount of cut and fill follows the formation principles of the material flow on the topography, assisting or mediating erosion and deposition processes.

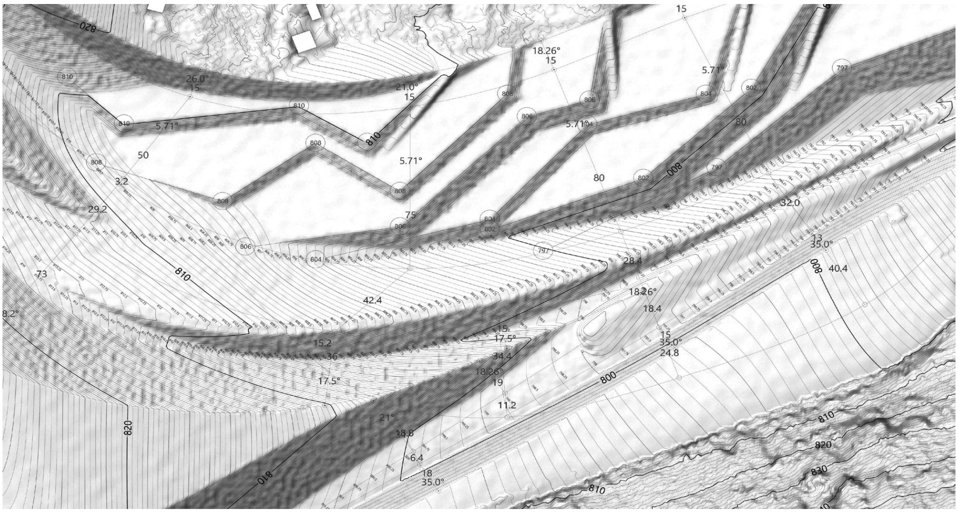


Figure 5.22: Using Docofossor, the topological model is translated to cut and fill operations to achieve a new topographic plan. By students Kelly Meng and Dawit Tadesse.

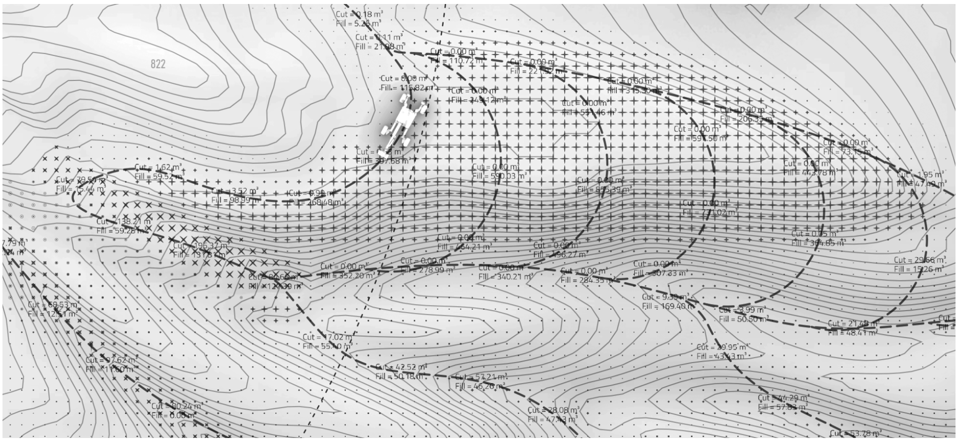
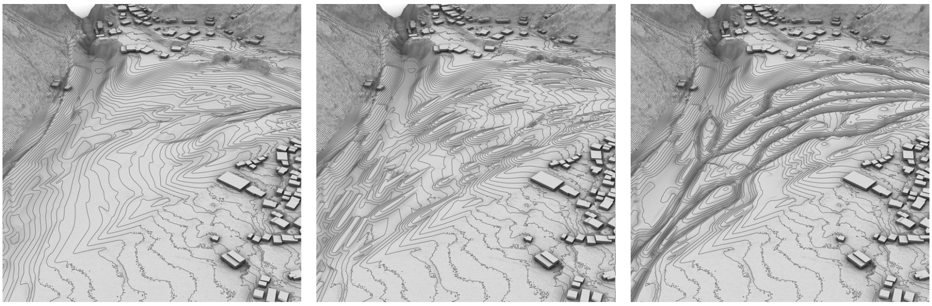


Figure 5.23: Robotic execution plan made visible: The fabrication constraints are taken into account in the robotic movement on site. By students Lip Jiang Lee, Matthew Lee, and Yorika Sunada.

Finding

While the robotic agency was modelled in an iterative fashion using Docofossor, the debris flows were simulated using RAMMS (see Section 5.3.3). Using simulation, a new design can be tested in the early design phases. This is important because natural processes in terrain are not very intuitive, and even expert assumptions can translate badly to a specific topography. By simulating early and frequently, designs evolve along performative and poetic dimensions side by side. This holds true for individual time-frames, but becomes fundamental for evolving processes. By applying the robotic mechanism—capable of responding dynamically to natural processes on-site—new forms emerge that were inconceivable before.

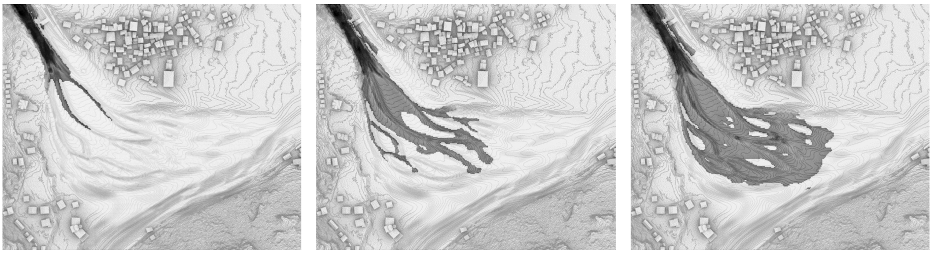


(a) T1: Balance 0 m^3 (b) T2: +150'000 m^3 (c) T3: +400'000 m^3

Figure 5.24: Evolution of the terrain where the robotic agency responds to—and directs—ongoing natural formation processes. By students Lip Jiang Lee, Matthew Lee, and Yorika Sunada.

Following up from Figure 5.23, Figure 5.24 shows how the site evolves under the influence of natural and robotic forces. Here, the robotic agency follows and directs naturally formed channels in the terrain, which would otherwise clog up and form a substantial hazard for Bondo. In Figure 5.25 we look more closely at a single simulation in T3 of Figure 5.24c. Here, the construction of an upper channel directs the debris flow beyond the village after 300 seconds. Now, the specific topographic embankments split and merge various material flows, which creates turbulence to slow the debris flow. After roughly 1200 seconds, the material stops moving and settles in a large detention area. This area has now become full of debris. By leveraging the robotic agency, this site can now be remodelled once again, in preparation of future debris flows.

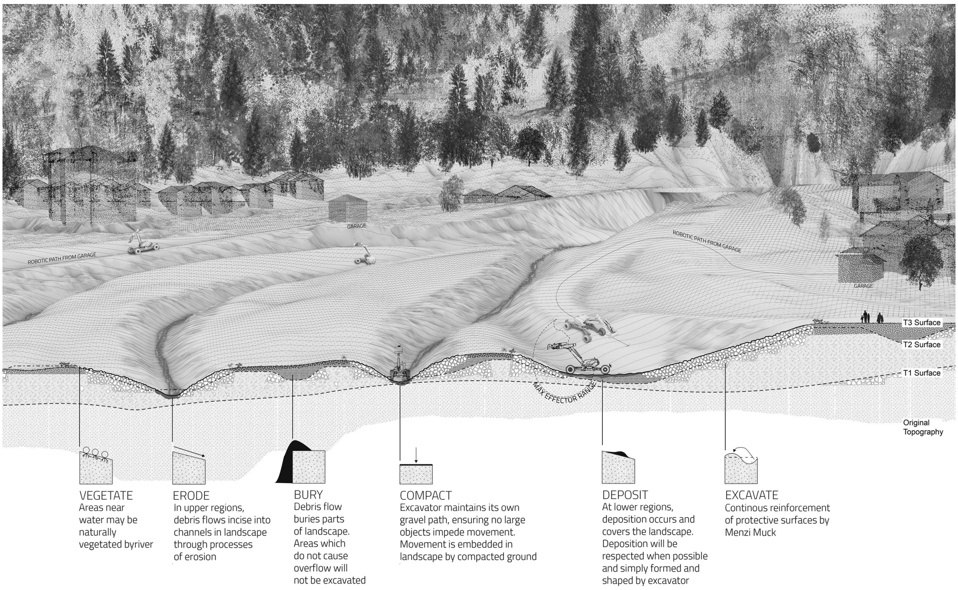
By proposing to station robotic equipment on the site, terrain processes can be maintained and controlled without the need for large and fixed control structures. Figure 5.26 illustrates this concept. At different time scales, the project is validated computationally using simulation as well as visually by embedding it



(a) Simulation time: 300 sec.
(b) simulation time: 600 sec.
(c) Simulation time: 1200 sec.

Figure 5.25: Single simulation of the debris flow in T3 at three intervals. The deposition depth ranges from 0.5 meters (purple) up to 8 meters (orange). By students Lip Jiang Lee, Matthew Lee, and Yorika Sunada.

into the larger point cloud model. Here, consecutive material layers form a new strata of sand, gravel, rocks, and boulder. While erosion, transportation, and deposition processes are ongoing, the robotic response promotes the stabilisation of embankments. By simulating future events, these embankments are strategically remodelled using cut, fill, and compaction operations to create a performative surface. Instead of a central hazard zone cutting through the valley, a continuous topography is created that re-connects the natural and cultural spaces present on site.



VEGETATE
Areas near water may be naturally vegetated byriver

ERODE
In upper regions, debris flows incise into channels in landscape through processes of erosion

BURY
Debris flow buries parts of landscape. Areas which do not cause overflow will not be excavated

COMPACT
Excavator maintains its own gravel path, ensuring no large objects impede movement. Movement is embedded in landscape by compacted ground

DEPOSIT
At lower regions, deposition occurs and covers the landscape. Deposition will be respected when possible and simply formed and shaped by excavator

EXCAVATE
Continous reinforcement of protective surfaces by Menzi Muck

Figure 5.26: Section perspective illustrating various natural and robotic processes on site, by students Lip Jiang Lee, Matthew Lee, and Yorika Sunada.

Results

Based on small scale physical experiments presented in Section 4.3.3, the integration of existing landforms and dynamic multi-material aggregation is established in an ever-changing topography. The landscape strategies were mostly concerned with the re-direction of debris flow events beyond the villages and onto the valley floor, where a moderate slope would allow for the material to settle slowly. Instead of creating a single detention basin (that had already failed in a previous event), sand, gravel, rocks, and boulders coming down from the mountain are re-distributed after each debris flow. As such, robotic earth-moving and natural erosion processes transform the terrain into a performative surface able to receive the ongoing material sedimentation on the valley floor.

To prevent future hazards, the newly created topographic structures were tested using rapid mass movement simulation in the RAMMS software package. By iterating over framing, forming and finding methods, ever-evolving topographies were easily modelled and validated. By describing the topography in a topological network using parametric and implicit methods, adjustment could be made quickly by changing a few parameters without the need of the laborious remodelling of BReps or meshes. Instead of only validating a single solution, the ongoing evolution in the terrain could be designed and presented.

More unexpected landslides and debris flow events are bound to happen throughout alpine regions due to the continuing effects of melting permafrost. The assumption that it is possible to create a static equilibrium, holds true only for short periods of time. While fixed and static defence structures may provide temporary safety, they are not able to respond to the ongoing natural processes in terrain. By using dynamic design and construction processes, ongoing insights from analysis and simulation can be incorporated in future structures. This enables an emergent transformation capable of adapting to ongoing processes in terrain.

5.4.4 Design Experiment 3: Open Ended Transformation

Object and Context: Erosion and Flood Prevention in the Gürbe Valley, Bern

The third experiment investigated a range of conceivable robotic approaches to make the Gürbe River in Kanton Bern more resilient. The Gürbe River runs in a valley between the Bernese Alps and Midlands, characterized by a distinctive lower alpine topography. The 30 km of the Aare tributary has challenging natural conditions and therefore an exceptionally tumultuous construction history. In the 18th century, the river appeared entirely different. The Great Gürbe Correction at that time enabled settlement and economic development in the lower stream. Despite the channelling of the Gürbe and the construction of 160 check dams to prevent erosion, flood damages could not be avoided and still today hydraulic protection projects are carried out without lasting effects. Furthermore, natural hazards in the Gürbe Valley have drastically increased in the last century. Long-lasting precipitation, in combination with the rapid melting of snow, triggers persistent floods and landslides. In 1990 heavy rainfall invoked a debris flow of over 200’000 m3 of material causing substantial damaged in the surrounding villages and destroying a significant part of the creek structures. After this event, the residual 60 barrage steps in the river were restored and reinforced once again to protect the settlement areas. In the last recorded event of spring 2018, 60 hectares of land became unstable in the upper reach, causing further damage to the check dams [154]. Looking carefully at the chronic disasters of the last centuries, it can be extrapolated that the number of hazards caused by floods and rapid mass movements will increase.

(a) Overview of the transitional zone

(b) Few of the many check dams

Figure 5.27: The debris cone in the transitional zone (a) and a close-up of the check dams in the Gürbe River (b, still frame by Benedikt Kowalewski).

Objective and Methodology

In response to the challenges of future catastrophes, this experiment questioned the concrete check dams that are expensive to maintain as they only last for about 20 years without thorough renovation. It aims to develop innovative approaches using only local materials while ensuring a long-term equilibrium in the river system. It continues to explore the potential of on-site robot construction and grading methods in landscape architecture with the application of the robotic mechanism applied to soil and rock. The goal of the studio was to define how

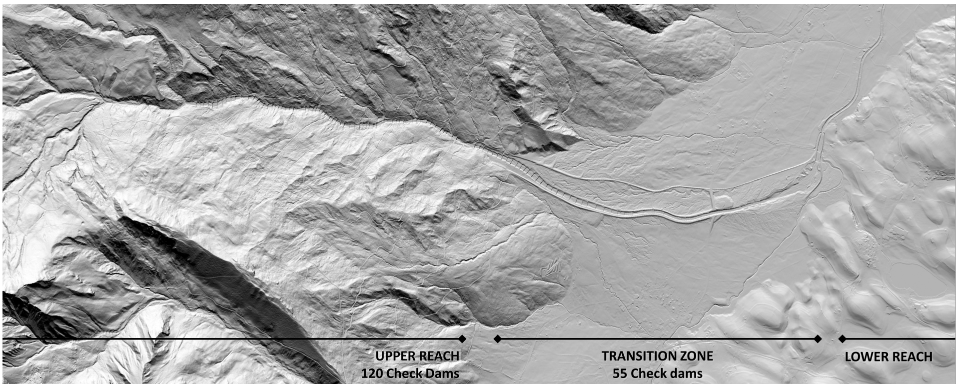


Figure 5.28: The upper and lower reach of the Gürbe River, with the transitional zone on the debris cone that has been formed over thousands of years.

the transitional zone (see Figure 5.28) of the Gürbe River can be reshaped using only local materials while creating a sustainable and resilient landscape in dynamic equilibrium. The design work followed the precepts of a dynamic design approach with an emphasis on precise terrain modelling. The design approach took into account the amplitude and dynamics of floods and debris flows in relation to topography and land use.

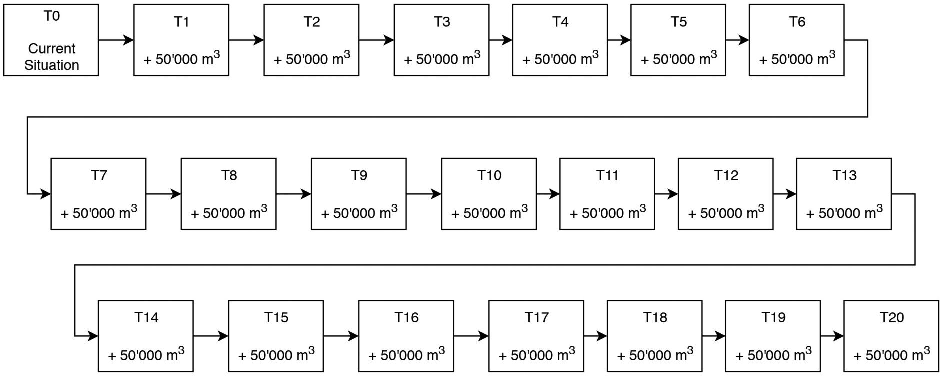


Figure 5.29: Expected material deposition coming down from the Upper Reach due to the collapsing check dams in the form of debris flows. Total material balance after 20 years is + 1 million cubature on the site.

Framing

The site of investigation was located on the debris cone that was formed through thousands of years of deposition, and the on-site material consists of mostly sand, gravel and cobbles. In the absence of large boulders, erosion and deposition processes are expected to be rather active. By suspending any maintenance on the 55 check dams in the transitional zone and another 120 in the upper reach, at least 5’000 m^3 of material per check dam will wash downstream. This comes on top to an increase in erosion, as the slope of the river bed will change from a rather flat profile established by the check dams to a profile that follows the slope of the underlying terrain between 3% to 10%. Since the upper reach had become unstable in 2018, more material is expected to arrive in the transitional zone as well. Adding all these material processes together, roughly 50’000 m^3 of sand, gravel and cobbles is estimated to sediment on-site per year, with a single maximum event holding as much as 200’000 m^3 (see Figure 5.29).

The natural processes on-site consist of debris flows and floods. As the floods are caused by the erosion of the banks as well as too much sedimentation in the lower areas, remediation measures focused on reducing the flow of the water by widening the stream as well as the promotion of erosion and sedimentation processes in areas where it wouldn’t cause any hazards. However, due to the constraints by adjacent villages and farmland, these measures would not create a lasting solution. The robotic processes were therefore conceived to maintain a resilient system over time. By using the same debris flow simulation software from the second design experiment, both erosion and deposition cubature were validated. To increase the economical aspects of material re-distribution, the location of erosion and sedimentation was chosen to maximize natural formation and minimize the robotic agency on site. Figure 5.30 shows how to prevent erosion using only granular material. By creating more space, making the path of the river longer (and thus less steep), and adding more friction in the river bed, similar flow rates can be achieved without the need for check dams.

However, the rate of erosion and sedimentation does increase by using only granular material. A continuous maintenance of the transitional zone is necessary that counteracts these processes which would eventually lead to an imbalance of the system. This was achieved by applying robotic formation strategies that were investigated in the small scale physical experiments of Section 4.3.4). They consist of dynamic distribution, goal optimization, responsive geometry, and open-ended formation. The application of these strategies enables formation process where the evolution of the terrain is directed by a second-order cybernetic system using combinations of procedural and topological approaches. All the robotic processes are based on the capabilities of HEAP, the autonomous walking excavator. Figure 5.31 shows the amount of material that one machine can excavate on its own[2]. By

---

[2] These numbers are based on the landshut-formula using manually operated excavators and separate haulers. It calculates the excavation potential based on motor power (m3/h = kW * 0.75). HEAP, a Menzi Muck M454 has 115 kW which amounts to 690 m3 per day. The experience from building the full-size embankment prototype with HEAP tells us that this number is very optimistic in a robotic application, especially when the same platform is also used to haul the material.

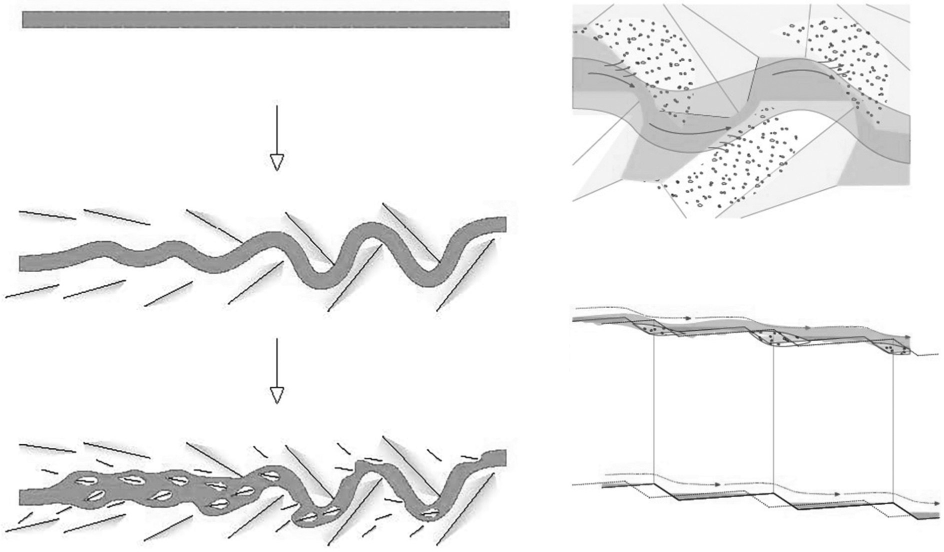


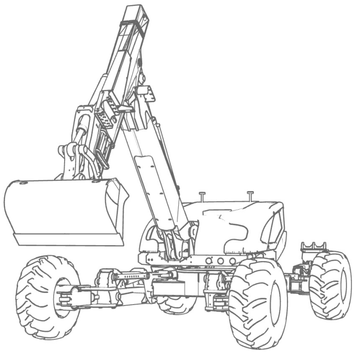
Figure 5.30: Natural and robotic design principles going from a straight channel to a meandering stream, while allowing space for debris flows. By students Caspar Trueb and Lorin Wiedemeier.

either increasing the number of machines or having it work throughout the year, enough mechanical power is available to re-distribute all the material that enters the site.

The underlying landform of the transitional zone is defined by a debris cone situated between the gorge in the upper reach and the almost horizontal grade of the valley floor. Because the channel and check dams were constructed on top of this debris cone, the natural flow direction fans outwards pointing directly to agricultural land and the villages of Mettlen and Blumenstein situated on either side. This created a challenging topological condition where the flow direction had to be steered towards the centre of the site. It primarily relates to the objective of an open and accessible landscape that re-connects the two villages and allows for a resilient ecological system. By analysing the terrain at various locations, specific topological solutions were proposed that incorporated the overall shape of the debris cone while adapting to local site conditions.

Forming

The design processes start with an initial investigation of topological prototypes that can serve as an alternative structure to the check dams. The goal was to slow down the river and create enough space to direct and collect debris flow mate-



‣ 1 Menzi Muck, 1year:	251‘850	m3
‣ 1 Menzi Muck, 10years:	2‘518‘500	m3
‣ 1 Menzi Muck, 20years:	5‘037‘000	m3

Figure 5.31: A rough estimation of the excavation potential of HEAP, by students Caspar Trueb and Lorin Wiedemeier.

rial (see Figure 5.32). Figure 5.33 shows an example of a prototype in continuous transformation. Starting with the initial fabrication, it is subsequently eroded and reconstructed again using the sediments that have accumulated around it over time. The embedding of the prototypes in the digital terrain model was achieved by absolute and relative modelling operations from Docofossor. Here, the prototypes were dynamically transformed based on the underlying landform. By inserting these topographic dividers in the digital terrain model, various solutions were found that were capable of mediating erosion. The orchestration of terrain structures followed the decreasing slope of the transitional zone where the steep upper slope requested different dimensions than the lower areas (see also Figure 5.35).

Most large-scale design approaches followed the precepts of a topological approach to robotic formation, where the geometry is defined as a dynamic and responsive surface. In one example, a purely procedural approach was applied. Here, all aspects of the design were encoded computationally. Starting from the landform analysis, the slope of the debris cone combined with the perpendicular distance to the riverbed determined the extent of the transformation. By strategically digging and dumping material on site, a “roughing” operation of the topographic surface was achieved able to slow down both water and debris flows. This caused various erosion and sedimentation processes, which formed the basis for subsequent emergent robotic formation. Figure 5.34 shows an attempt to model this process in the large-scale digital terrain model using only relative modelling operations, provoking a new language between forces and forms in terrain.

Figure 5.35 displays the evolution of the transitional zone over 20 years. It starts with the existing situation where the 55 check dams ar still in place. By reusing the local material from the channel walls, the first structures can appear on site that promotes material sedimentation, which is subsequently used to extend

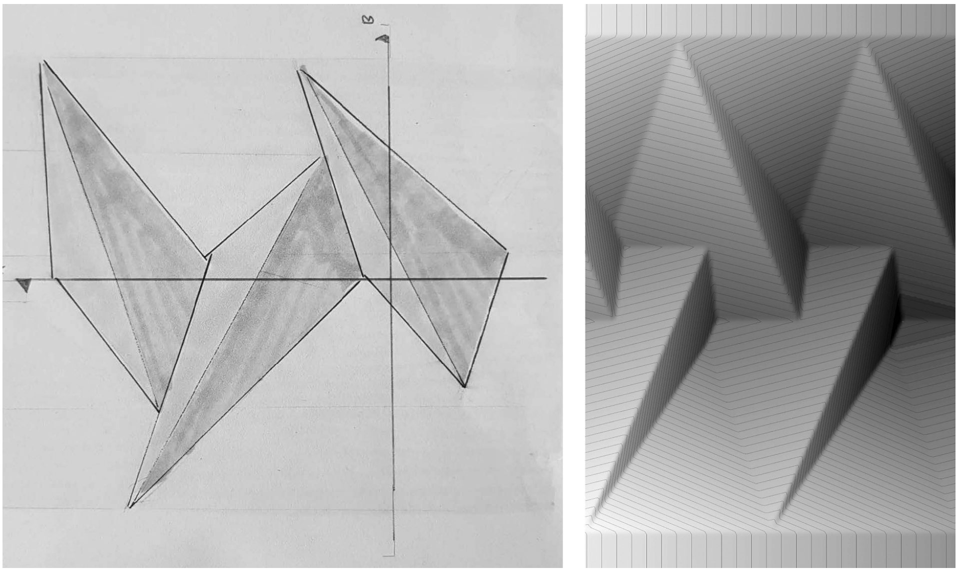


Figure 5.32: Topographic prototype designed to slow down the river and the debris flow without the use of check dams. By students Caspar Trueb and Lorin Wiedmeier.

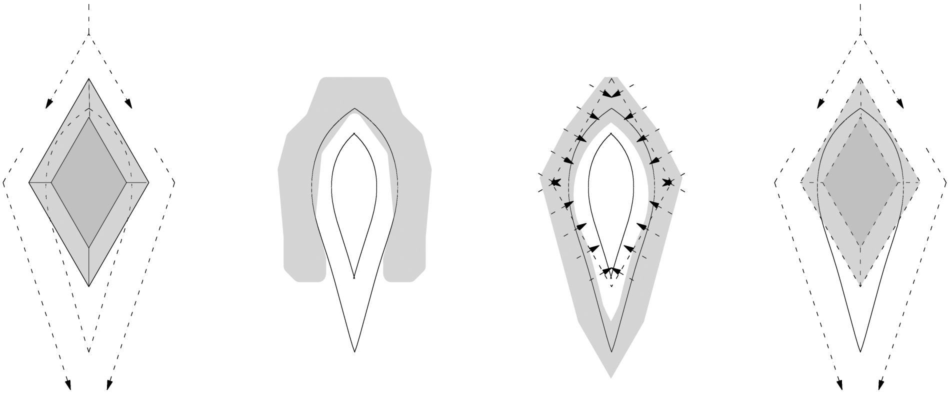


Figure 5.33: Prototype as a sacrificial landform that is able to disperse and attenuate the energy of the debris flow. By students David Brückmann and Mevion Famos.

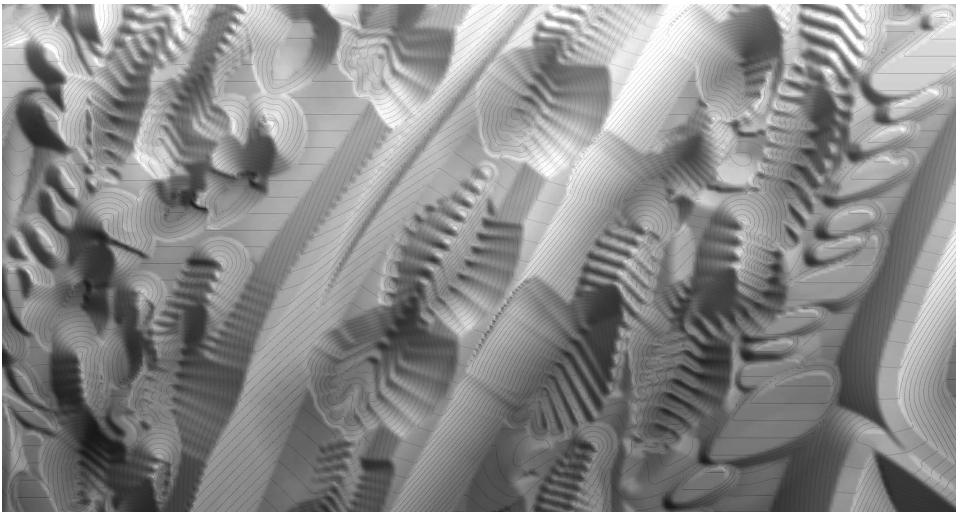
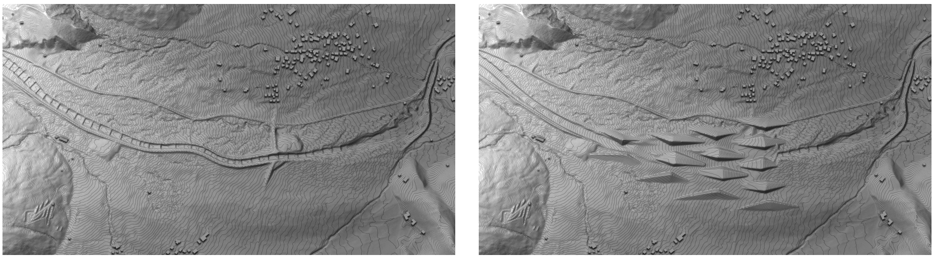


Figure 5.34: Topographic plan using only relative operations in Docofossor to mimic digging and dumping cycles of the robotic process in the topography. By students Leo Graf and Hannah Kilian.

the system further. These initial structures also direct any overflow by reinforcing the border conditions and creating side-streams to contain the debris flows. As more material arrives from erosion processes in the upper reach, the terrain continues to grow over time. Because the structures are eroded themselves, they can re-appear on a different location for economical reasons in material distribution. At this point, the transitional zone is capable of safely receiving 200’000 m3 debris in a single event. The following evolution is rather speculative and open-ended, as the scale of the intervention relates directly to the amount of erosion in the upper reach, and the amount of sedimentation in the transitional zone. One possible outcome is depicted in Figure 5.35d, where the system continues to grow upstream and expands outward.

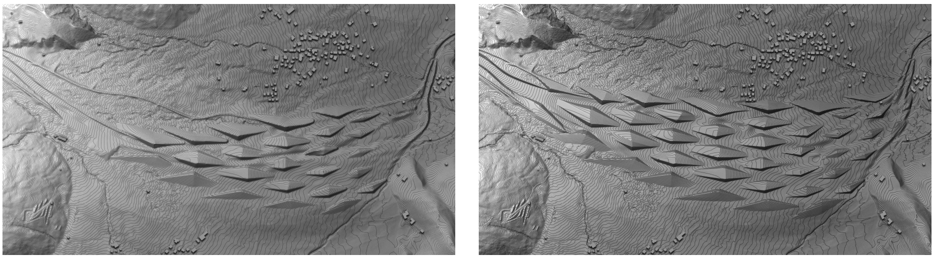
Finding

Using rapid mass movement simulation, the embedded prototype is tested iteratively during the design process. Figure 5.36 shows the design process over 12 iterations. It is clearly visible that the first implementation failed dramatically with the debris flow spilling out on both sides towards the villages (top left). The following iterations were optimized so that sedimentation processes would spread evenly over the site, minimizing impact pressure and subsequent damage to individual embankments. This includes the understanding of flow rate (more erosion) and flow pressure (more erosion) in relation to the form of the embankment. By decreasing the slope of the impact-side, structural strength in the form of large



(a) Existing situation

(b) After 5 years



(c) After 10 years

(d) After 20 years

Figure 5.35: The evolution of the topography over 20 years through the interaction of natural and robotic processes on site, by students David Brückmann and Mevion Famos.

boulders or concrete can be avoided. In looping over framing, forming and finding methods, the prototype evolves into a new landscape structure that is capable of directing and storing all the debris flow material. The application of a varying state-goal within the system also enables an intelligent material distribution. Through analysis of the material volumes, individual embankments are either restored or—in case of extensive material transportation due to natural forces—rebuild in a new location. This is made possible because the embankments are only defined on a topological level, which can be adjusted parametrically. Therefore, the final topography, as rendered in Figure 5.36, is only the result of implicit operations in the DTM. However, a change in topology requires another simulation to validate the newly modelled topography.

Because any new structure only uses locally available sand, gravel, and rocks from the site, a continuous observation of the cut and fill balance is necessary. Apart from the tools provided by Docofossor, a cut and fill analysis as seen in Figure 5.37 provides visual feedback in every step of the design process. It is immediately apparent that the extra material from the upper reach enables an entirely new structure without the need to disturb the terrain from the surrounding land.

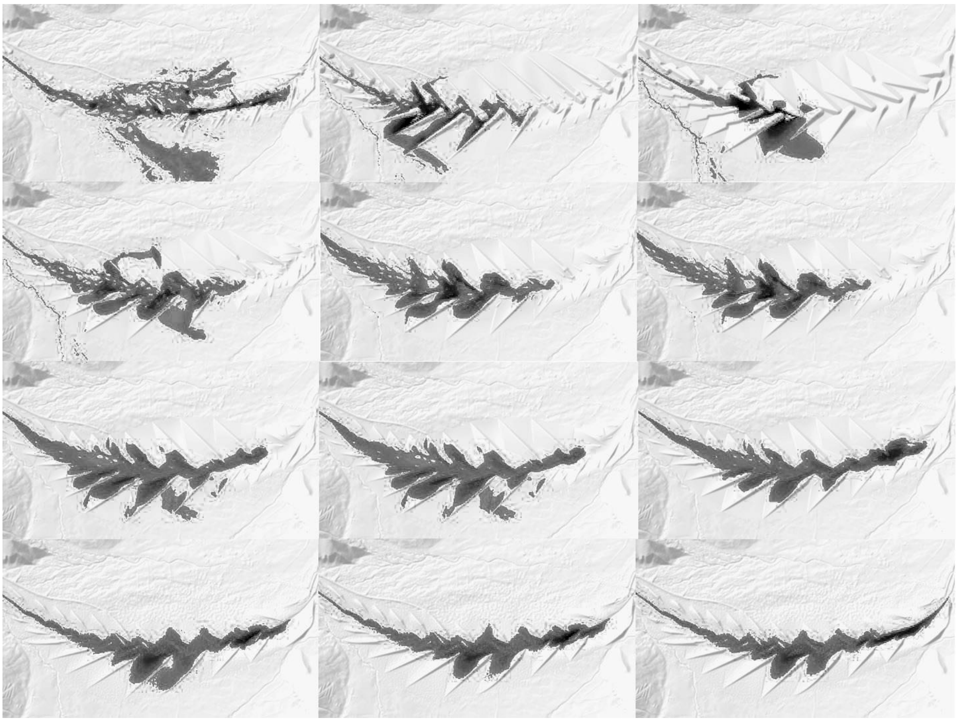


Figure 5.36: Twelve simulations over the course of the whole design process. The first topographic design clearly failed, and was continuously adapted using input from the simulations to come to a valid landscape structure. By students Caspar Trueb and Lorin Wiedemeier.

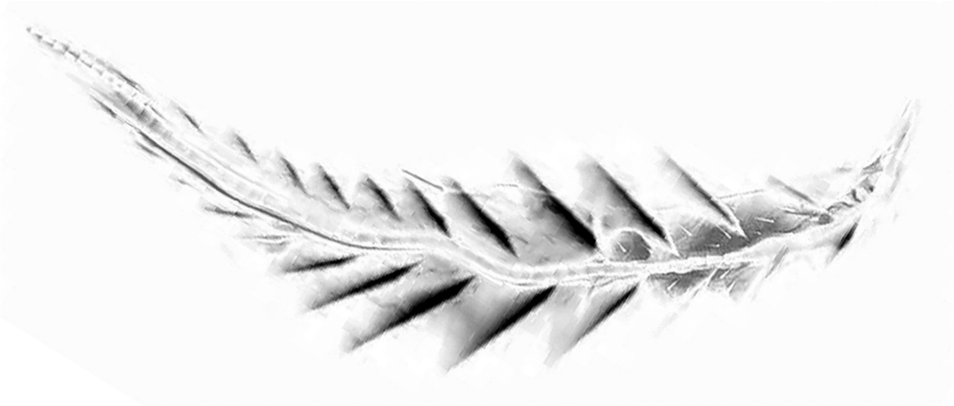


Figure 5.37: Cubature balance of the design after 20 years of formation between cut and fill, including the addition of 1 million cubic meter of sedimentation from the upper reach. By students Casper Trueb and Lorin Wiedemeier.

Results

The natural progression of the debris cone in the transitional zone—formed by a dynamic process over thousands of years—is rendered statically by building check dams in the effort to prevent natural hazards. Instead of defining a single formal goal that should conceptually last forever, flexible state-goals take the site-specific formation processes into account and are able to continuously respond to changing local conditions (due to dynamic equilibrium). As the continuing deterioration of the existing check dams in the transitional zone of the Gürbe River poses severe hazards to the local community, this design experiment applies robotic construction techniques to establish a resilient and sustainable landscape structure. Using reflexive design methods, a dynamic response in a natural system was validated. The robotic agency, explored in the third formation experiment and described in Chapter 4, dynamically re-distributes granular material, optimises procedural and topological goals in response to natural erosion and sedimentation and promotes emergent formation principles by understanding the natural forces acting in terrain. These open-ended strategies are essential in creating a resilient terrain that is able to perform over long time periods. As such, robotic formation in natural granular material can form a soft and sustainable alternative to concrete check dams.

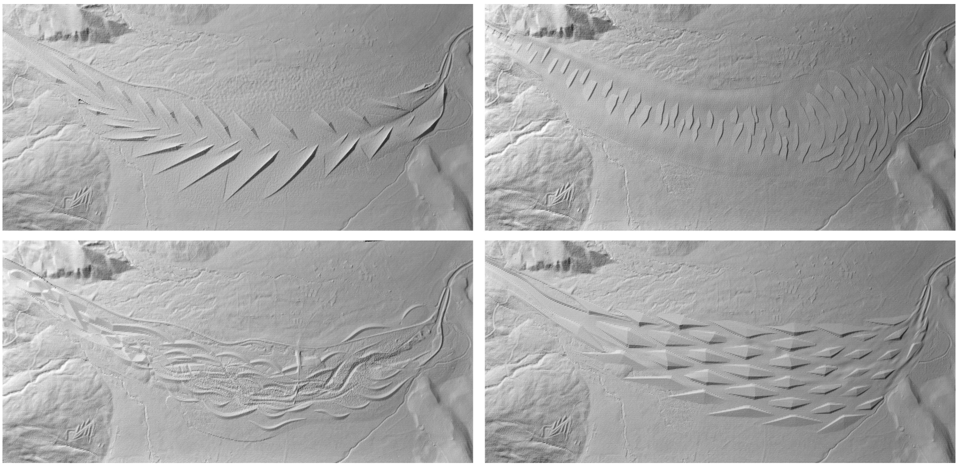


Figure 5.38: Physical CNC models of the topography after 20 years in very different topographic solutions. By students David Brückmann, Mevion Famos, Nicola Graf, Sakiko Noda, Wei Wei Toh, Caspar Trueb, Lorin Wiedemeier, and Yueye Xu.

Figure 5.39: Section-perspective visualizing the landscape after 20 years of robotic and natural processes acting on the site. By students Caspar Trueb and Lorin Wiedemeier

5.5 Summary

This Chapter explored large-scale and dynamic landscape topologies in terrain using robotic construction processes. A reflexive design process is recognised where the material system directly informs the progression of a robotic response. Here, the terrain is not only transformed through a dynamic grammar in earthmoving, but changes continuously due to natural processes as well. This changes the role of the designer as a mediator between natural and robotic agencies. Instead of defining a final geometry as a product of the mind 2.2.1, it forces the designer to think about—and design—processes of formation.

The robotic mechanism enables the analysis and manipulation of natural granular material. A site-specific approach is enabled by iterating over surveying, modelling and simulation methods using topological and procedural rules. As terrain is chaotic in nature and inherently unstructured, a topological approach is able to inform this loose and granular material so it can be imagined and validated. The digital modelling tools from Docofossor facilitate the translation of nodes, lines and regions of a topological network in a topography with dimensions in Cartesian space using primitive landform descriptions. By encoding the network parametrically, design iterations, adaptive responses, and evolutionary concepts can be conceived.

By defining constraints based on material, progressive, fabrication, and topological variables, a design system is proposed for dynamic formation in terrain. These design processes and methods were formed during three design experiments with varying object and context. Based on point cloud surveying methods and digital terrain models from the Federal Office of Topography swisstopo, site-specific spatial data formed the basis of all dynamic design proposals. Through topological modelling, local materials were transformed into new performative structures while balancing cut and fill. These transformations in terrain were conceived as robotic formation strategies relating to dynamic, emergent and open-ended concepts based on the small scale robotic experiments in a sandbox. The implementation of numerical simulation software validated the natural processes acting in terrain. Various time frames and amplitudes of the debris flows were tested to come to a new dynamic equilibrium between natural and robotic forces on site.

As climate change has a continuing effect on the dynamic equilibrium that exists in natural systems, existing methods to protect cultural landscapes from natural hazards are questioned. The design experiments showed that it is possible to conceive a dynamic response to dynamic environments using robotic technologies. Through adaptive transformation, local and natural materials were able to form a protective barrier against sound pollution in the first dynamic design experiment. The second experiments showed how emergent structures could mediate the ongoing evolution of erosion and sedimentation by redirecting debris flows away from urban areas. Finally, open-ended strategies were applied to erosion prevention and flood control in the third design experiment, where 55 concrete check dams were replaced with a new and dynamic infrastructure made out of sand, gravel, rocks. These experiments demonstrate that a robotic agency is capable of managing local material sustainably while creating resilient and performative terrain structures.

As design can drive technology just as technology enables new design solutions, this Chapter describes the design experiments that were initiated to explore the potential of newly arriving construction processes. In turn, these experiments propelled the development of digital tools (see Chapter 3) and dynamic fabrication strategies (see Chapter 4). Through the design experiments in this Chapter, design processes and methods were developed to explore and validate the agency of robotic fabrication in landscape architecture. This resulted in the formulation of new strategies that rely on dynamic maintenance in terrain. The continuous formation of terrain between natural and robotic forces is therefore capable of reacting to changing site conditions due to shifting climates. By designing new topological rules for forming terrain, a newfound dynamic equilibrium can be achieved between solid and fluid states of matter.

Chapter 6

Conclusion: Terrain Moves

> *"Picture in your mind's eye the sand box divided in half with black sand on one side and white sand on the other. We take a child and have him run hundreds of times clockwise in the box until the sand gets mixed and begins to turn grey; after that we have him run anti-clockwise, but the result will not be a restoration of the original division but a greater degree of greyness and an increase of entropy."*
>
> —Robert Smithson [155]

6.1 Overview

The research set forth in the previous chapters is aimed at dynamic, ongoing strategies for working with terrain. Instead of ready-made, static solutions it opens the possibility of a landscape in continuous transformation. This Chapter will discuss the results of the dissertation and will give an outlook on the future of topological methods in digital landscape fabrication. By focussing on landscape topology and robotic fabrication, new tools, design processes and formation strategies were developed throughout this research. While they were specifically developed for robotic fabrication, the modelling tools and processes also provide tools and insights for the broader field of landscape architectural design. Therefore, the following Chapter focusses both on robotic fabrication as well as digital technologies for landscape architecture as a whole. The Chapter will start with an overview of the work form the previous Chapters by discussing their results and limitations. Here, the four core concepts and their design and construction constraints form the basis of a dynamic design and fabrication method in terrain. Looking at the integration of models of information, design and fabrication, current challenges and future opportunities are outlined. This is followed by a discussion on the potential of robotic landscapes. Due to the collaborative nature of this research, the contributions also list the people and institutions that were instrumental to this dissertation. The Chapter is concluded by a future outlook to research and design.

6.2 Landscape Topology and Robotic Fabrication

6.2.1 Four Core Concepts

Throughout Chapter 4 and 5, four core concepts of formation are defined as substance, process, grammar and form. As a local and site-specific approach has many advantages in ecological, economical, and symbolic aspects, the physical substance of a site forms the starting point for any transformation. It informs and determines the possible terrain structures and formal expression in horizontal and vertical dimensions. The found material on the site can gain new functions and performances through topological transformations. The performance of a landscape over time is related to the natural processes acting on it. They vary widely in time and scale, ranging from chemical weathering and sudden hazard events to slow but ongoing material transportation in large watersheds systems. They one thing they have in common is that they are never static, ever in motion in dynamic equilibrium. Robotic construction affords a dynamic response to these processes, evolving over time, together with the changing terrain. This artificial ’second’ force is enabled by autonomous machines capable of moving material using the grammar of earth-moving. The movement of a bucket through terrain transforms granular material into a new structure. Just like natural processes, time and scale determine whether a new equilibrium can be achieved between natural and robotic processes. Finally, the form of the terrain is both the starting point and the result of all previous concepts. This reflexivity determines—and is determined—by the natural and robotic processes in granular material.

Robotic Earth-Moving Constraints

The four concepts form the foundation for a topological design and construction approach in terrain. In Chapter 5, we have seen that the definition of a precise, final geometry does not have to be the primary driver for working with loose and granular material. Working with earth allows for a variety of formal expressions that are rarely position-critical in the use or the performance of the landscape. Instead, terrain structures operate in relation to where they are positioned to other structures. An abstract and relational understanding in landscape topology is therefore beneficial. Furthermore, large-scale landscapes are not only influenced by the behaviour of the material itself but is also under the influence of natural processes acting on it. In order to define an appropriate design and fabrication methodology, this dissertation identified four constraints: 1. material constraints, 2. progressive constraints, 3. fabrication constraints, and 4. topological constraints. These constraints should allow the terrain to evolve over time without breaking the goals or integrity of a project.

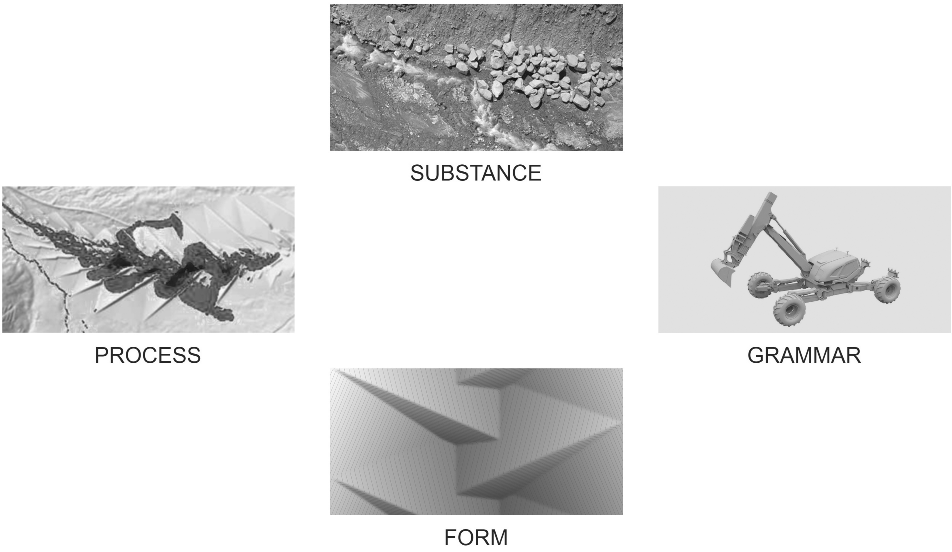


Figure 6.1: The four core concepts to digital landscape design and fabrication in terrain.

This research has implemented tools and methods to translate the design and construction constraint of Figure 6.1 towards the development of a computational design system. Substance is the material at hand on site, relating to the material properties of terrain that vary by its soil texture and mechanical properties. Process is defined by the natural processes that actively change the configuration of the terrain, and describes the progressive change over time (like erosion and sedimentation). Grammar describes the workspace and the shape by which material is manipulated and distributed by the robotic platform. This was explored in small scale robotic sandbox experiments and by an embankment prototype using HEAP. Finally, the form of the terrain encompasses the functional constraints and aesthetic valuation of the landscape, explored in the three design experiments. While these constraints may never be comprehensive, it provided ways to conceptualize and experiment with robotic fabrication and explore its potential for landscape architecture. This dissertation recognizes two important dimensions in Figure 6.1; substance and form relate to the scale of terrain, while process and grammar belong to dimensions of time. As such, the vertical axis (substance and form) defines the structural nature of terrain that depends on the scale of the application. Here, appropriate tools and methodologies have to be chosen accordingly. The same applies to the horizontal axis (process and grammar), where the forces acting on terrain can be only be conceived through a time-based approach. The following Section will discuss and conclude on the results of this research, and elaborates on the application of these four concepts and how they translated to tools and methodologies for digital design and fabrication in landscape architecture.

6.2.2 Integrating Models of Information, Design, and Fabrication

Ever since the introduction of digital information systems and computer-aided landscape architectural design, there has been a schism between the models of information (GIS) and the models of design. While there have been many efforts to close this gap by linking these two paradigms, only rarely do they enable a dynamic relation to each other. The introduction of mobile and on-site robotic equipment closes the gap between the world of design and construction. Here, a direct link is established between the design model and the fabrication instruction. Because the natural environment is in constant change, and robotic systems in terrain follow a procedural construction approach instead of moving along a pre-defined path, the information model has to be updated dynamically. It is therefore evident that the convergence of information, design and fabrication is a pre-requisite for on-site robotic construction.

Dynamic Terrain Modelling Tools

With Docofossor, this thesis developed terrain modelling tools that operate directly on a raster DTM using distance functions. This implicit modelling method allows a continuous data stream between the survey, the design and the fabrication without conversion to meshes or NURBS. From a terrestrial or areal laser scan, an elevation map is created that is sent to the design environment (see Section 4.4). Because this data is segmented and filtered into a raster map [117], Docofossor can read it without any conversion. From here, the operations in cut and fill create a new landform by setting various parameters for the distance functions. Since the design model is parametrically defined, additional sensing data and landscape analysis is able to update this model dynamically. The same elevation data can again be validated easily, as most computational packages use raster grid data as a base for the simulation. After this step, the elevation data flows back to the robotic platform, along with other attributes like path planning instructions. While this process has been demonstrated successfully in the experiment with HEAP, there are many limitations that need attention. The attribute model that is so powerful in GIS has not been fully implemented, and the question remains whether this has to be included in Docofossor as a multi-layer approach, or to establish a separate information model independent from the free-form CAD environment. This would also enable the use of existing point cloud editing tools (like the Point Cloud Library [156]) for the segmentation and filtering of incoming lidar scans into raster DTM's.

The Need for Computational Topology

The *shapes* and *motions* approach in Docofossor on point, path and areas provide tools for cut and fill operations. However, these pre-encoded primitives still proved to be a limiting factor in the freedom of expressing landform between natural and robotic processes. Additional primitive descriptions and a generative algorithm library (like the sinewave and noise components already implemented) would therefore be necessary. Dynamic form-finding tools, where the terrain is iteratively tested and adjusted computationally, rely on a computational landscape topology to assess the terrain structure as well as a discrete landform description. This is necessary because the unstructured nature of terrain data does not allow for pre-defined structural clarity that can be tested. Because Docofossor uses point, lines and areas as its base-geometry for the operations, it is well suited for a topological implementation in a network structure. However, a digital and topological landscape description has not been developed yet, and the designs discussed in Chapter 5 still relied on analogue interpretation and intuitive adjustment by the designer. There are still many challenges to overcome for a topological landscape description. The classification of landforms are mostly based on similarity in morphometric characteristics on individual cells without a spatial understanding of its structure [69]. To think about computational landscape topology would therefore first and foremost rely on the development of a comprehensive description of land surfaces based on its structure.

Another point of attention is the interoperability with existing analysis and simulation tools. There already exist many analysis and hydrological or mass movement simulation solutions that only rely on a DTM, though they are generally conceived as stand-alone software packages. A stand-alone programming framework that implements the digital terrain modelling tools of Docofossor would therefore streamline the data flow between the design model and the tools they provide. However, these tools would be geared towards research, as most landscape designers do not have the skills to develop designs in code alone. A continuing development of a dynamic design system that includes material and machine computation (see Section 2.3.3) while allowing the free-from editing of the terrain, will become a necessity to benefit not only developers but also future landscape designers. Enabling dynamic interacting with natural processes in terrain within the design environment becomes an absolute prerequisite for resilient landscape design in light of the current ecological situation.

A Grammar of Earth-Moving

Earth-moving is an inherently dynamic process. As digging and dumping cycles evolve, the unstable and granular nature of terrain demand continuous observation to respond to the changing material conditions. While autonomous machines move over unpredictable terrain, localisation and mapping enable dynamic tool movements that are adjusted to the current position and state of the material. Without the robotic mechanism, this would be impossible to achieve. The separation of operations in digging, transport and dumping motions create a syntax of individual bucket-motions that over time establish a transformation in the aggregation of granular material. While the individual sub-goals of the operation cycles are best defined procedurally (dynamic decisions made based on elevation data to decide where to dig and dump), an overall state-goal is best defined topologically. Through continuous sensing technology, the state-goal can be adjusted dynamically, for instance, based on ongoing cubature balance or observed slope stability. The small scale experiments of Chapter 4 demonstrate how purely procedural, topological, or combinations of these approaches can be applied. While the operation cycles need dynamic feedback after every digging or dumping motion, the overall topological state-goal can be adjusted less frequently based on the site and project itself. As natural process tend to have longer time-frames than a typical construction project, this can vary between a few minutes to many years of observation as explored in the large-scale design experiments discussed in Chapter 5.

From the side of digital fabrication, efforts have been made by Gramazio Kohler Research in the development of RosLibPy [157] and COMPAS FAB [140] that enables the communication between the widely used Robotic Operating System (ROS) [158] on Linux and the free-form modelling environment of Rhino on Microsoft Windows as well as the parametric modelling tools provided by Grasshopper. These tools have been implemented in the robotic embankment prototype to send elevation and path planning data back and forth between the design environment of Docofossor and the robotic platform HEAP. This setup has worked very well for the topological approaches of the robotic landscape formation experiments, but is not robust enough to directly control the machine's movements from within the design environment. However, separating a procedural approach that is applied to individual digging and dumping cycles while maintaining an overall formal description of the terrain (that is dynamically adjusted based on changing site conditions) at the larger scales has proved valuable. Without this formal description, robotic processes would be an independent force in the landscape, but also very difficult to control.

The Limits of Autonomy

The application of dynamic construction processes using autonomous machines is informed by the design and construction constraints. Without a topological description of landforms, state-goals are difficult to control or tested on its performance in terrain. Using a second-order cybernetic system, where the state-goal can be adjusted in-place through a reflexive process, a comprehensive constraints model could theoretically contain all the necessary components for full automation over long periods of time. The most uncertain condition lies in evolving insights and demands from public requirements. While robotic processes can provide continuous landscape maintenance in response to physical processes, the state-goal as defined by the designer at the moment of conception will inevitably change due to progressive insight. As such, robotic construction forces a shift from designing that which is known to that which is unknown, and should allow future readjustment. It shifts the object of design towards a time-based a conception: from 'what' needs to be achieved to 'when' it needs to be achieved. Just as the landscape will never be finished, the design can never be considered final.

6.2.3 Dynamic Landscape Design and Fabrication

Through the use of on-site robotic construction processes, landscapes become informed not only by natural forces but by mechanical actuation as well. While there exist many examples of robotic systems governing and altering landscapes (mostly oriented towards the direction and chemical constitution of water bodies [159]), never before have they been mobile. This section will discuss how observation and fabrication instruments can direct the form and forces in terrain.

On-Site Materiality

With the ever-increasing superimposition of natural and infrastructural systems, the material make-up of terrain becomes increasingly complex. The resilience of ecological systems in natural granular material depends on its ability to recover from disturbances through self-organization and resurgence. By applying point cloud technology and robotic processes, it becomes possible to understand and respond dynamically to highly local material differences in terrain enabled by various sensing instruments and landscape analysis tools. Through computation, an ideal earth-moving scenario can be achieved by understanding the available materials and dynamic equilibrium of a site. As such, the material constraints are not a limiting factor in design freedom, but an opportunity for a sustainable material culture in landscape practice. This not only has positive implications on ecological and economical levels, but it also creates a critically-local approach aimed at uncovering and strengthening the physical nature and meaning of a site.

The material make-up of terrain is best described as non-homogeneous. Grain size and soil profiles vary wildly, especially in previously disturbed site. The understanding multi-material environments and its influence on ecology is still challenging to describe in ecological or mechanical models. The potential of a site-specific response in robotic systems rely on a digital description of these environments. While the layer-approach in GIS has enabled the connection of attributes, a volumetric approach in terrain would allow for a complete digital model. As the scale of natural systems far extend existing volumetric modelling applications, these models will rely on future developments in computer power to make them available for design. This has been one of the reasons for Docofossor to stay within a 2.5D representation of terrain instead of a full three-dimensional approach in implicit modelling methods. Encoding terrain as multiple elevation layers does provide a workable solution and aligns itself nicely to soil horizons and robotic fabrication environments.

A New Equilibrium

Digital methods applied to construction marks a shift away from Albertian modes of design (void of materiality and only a concern of the mind [34, p. 93]), towards one that is actively acknowledging processes of formation [160, p. 126]. As computational methods inform the designer on the evolution of the natural material systems, mobile robotic platforms enable a dynamic response to ongoing processes in terrain. This opens up a whole new way of conceiving and designing a landscape, especially in regard to control and maintain evolving processes. However, the ability to send robotic machines in the landscape may vary depending on site, and many natural processes might be too slow for the lifespan of any robotic platform. The design experiments in Chapter 5 have shown how static infrastructure like river channels and dams can be replaced by a soft topography made out of local sand, gravel and boulders. Within a set perimeter, robotic forces were positioned to modify and transform terrain over time. This is made possible by an evolving understanding of the landscape topology and implementing robotic maintenance strategies that provide the necessary levels of control to keep these dynamic systems in equilibrium. Terrain structures not only counteract natural forces and provide safety, but they can also leverage erosion, transportation and sedimentation processes to its advantage by strategically aligning with—or opposing—flows of material. As the necessity of maintenance only comes forth out of public interest, interventions can equally be tuned to this need.

Reconciliation between Form and Process

The opposition between form and process in landscape architecture is evident in its education, aligning with either schools of design or the natural sciences. It also still permeates landscape thought today by contrasting the natural with the artificial. As this distinction is rapidly losing its meaning in light of the Anthropocene, a convergence of formal and ecological attitudes holds potential. With the advent of autonomous earth-moving equipment that operates explicitly in procedures over time, it becomes clear that form is nothing but the state of a system at a particular moment in time [24]. Therefore, form and process are inherently linked in the progression of terrain. As the underlying form of the landscape directs the flow of water and earth, so do these processes change the form itself, shifting towards a redefined equilibrium. By focussing on the performance of terrain, both as an ecological system and as a space for people, new possibilities may arise between the forces of design and the forces of nature.

In robotic landscape fabrication, a new structure in terrain is achieved in the combination of material and machine computation. The self-organisation in granular material forms a topological structure and landform, which is analysed and responded to dynamically using robotic actuation. While the tectonic in architecture can be described as the art of expressing forces acting in a material system, the tectonic in landscape architecture can be characterised as the art of expressing processes in terrain. By designing topological rules, a new topography emerges as a dialogue between the designer, the natural processes, and the grammar of robotic earth-moving.

A Chronology of Terrain

Terrain is in constant motion. It is formed by process over millions of year that extend far beyond a human time-scale. Throughout history, working with terrain has always been fundamental in support of civilisation. The recent increase of extreme natural events that can be traced back to climate change and call for an increased focus on the structural organisation of our terrains. At the extremes, we find a total retreat to safe ground or total control. While the second option has been tried and tested over the second half of the 20th century, it has left us with an increasingly uncertain environment causing destruction without capacity for self-regeneration. Modifying dynamic environments poses the problem of the impossibility to foresee its future evolution as computation and simulation are only able to reflect a small subset of the parameters involved in natural systems. Through dynamic construction processes, a continuous adaptation of terrain becomes a possibility. As such, the formation of terrain by natural and mechanical forces can evolve in ever-changing site conditions, capable of adapting to future needs.

Figure 6.2: Illustration of autonomous walking excavators working in terrain.

6.3 Contributions and Credits

Responding to the objectives of this dissertation set in Section 1.2.2, these paragraphs give an overview of the contributions towards the growing research field of digital fabrication in landscape architecture. The granular research process was based around three main areas of investigation: digital tools, robotic formation, and dynamic design. Research in the potential of on-site robotic earth-moving processes was facilitated in the development of digital terrain modelling tools. By integrating models of information, design and fabrication, robotic processes were tested physically in model- and real-world scales. And finally, in the topological approach, dynamic design strategies were developed to conceive applications for large-scale robotic landscape fabrication in terrain.

Contributions relating to digital terrain modelling:

Starting with the survey, the implementation of a lightweight aerial lidar scanner enabled the acquisition of precise elevation data. The integration of the aerial platform and the lidar scanner was done in collaboration with Dominic Jud from the Robotic Systems Lab of Professor Marco Hutter. In collaboration with Mathias Bernard from Digital Building Technologies of professor Benjamin Dillenburger, implicit methods using distance functions for digital terrain modelling were developed. These distance functions operate on points and curves to enable a topological modelling approach. It granted the development of the plugin Docofossor for Rhino 3D, a digital terrain modelling tool in the graphical programming interface of Grasshopper. The plugin allows free-form modelling while leveraging a parametric approach. Docofossor has been applied in two design research studio's, as well as in workshops and teaching in external landscape programs, and forms the basis for the design and fabrication of the robotic embankment prototype.

Contributions relating to robotic fabrication in terrain:

By assessing the substance of terrain and a robotic earth-moving grammar, material and fabrication constraints are formulated towards a constraints description in digital landscape fabrication. Based on the small scale formation experiments in collaboration with Ammar Mirjan and Jesús Medina Ibáñez from Gramazio Kohler Research, dynamic formation strategies in natural granular material are defined between procedural and topological approaches. In the development of the embankment prototype, a topographic approach was explored using various robotic fabrication tools were developed to facilitate communication between the design environment and the fabrication platform. It integrates the modelling tools of Docofossor in Rhino 3D with the Grid Map package in ROS to exchange real-time elevation and path planning data, e.g. The tools are built on COMPAS, a computational framework for collaboration and research initiated by the Block Research Group where the extension COMPAS FAB by Gramazio Kohler Research provided the necessary tools. The robotic embankment prototype was made possible in collaboration with the Robotic Systems Lab of Professor Marco Hutter, where Dominic Jud addressed the execution of the embankment prototype with HEAP.

Contributions relating to dynamic design in terrain:

By assessing natural processes in terrain and developing formal methods for encoding and modelling landforms, progressive and topological constraints are initiated towards a constraints description in digital landscape fabrication. They are investigated using reflexive design processes and through the development of dynamic design methods. These design processes and methods help conceive design solutions that apply digital landscape fabrication technologies. Here, dynamic design strategies are facilitated by the development of computational methods. In collaboration with Brian McArdell from the Swiss Federal Institute for Forest, Snow and Landscape Research, rapid mass movement simulations were implemented. Applications for digital landscape fabrication are established between adaptive, emergent, and open-ended strategies. They are based on design experiments to large-scale landscape fabrication carried out in collaboration with Fujan Fahmi and Benedikt Kowalewski of the Chair of Landscape Architecture, professor Christophe Girot. The potential of digital landscape fabrication is recognized in its ability to mediate between natural and human-made processes over time. Based on dynamic and topological modelling methods, the landscape applications demonstrate a new material culture and resiliency in the design and formation of terrain.

6.4 Outlook

Landscape architecture is about our design on the natural world. Enabled by the integration of material and machine computation, robotic construction processes allow an informative approach that is able to mediate between form and forces in terrain. A focus on computation for landscape architectural design is therefore not only logical but necessary as well in light of current climate conditions. This research contributed to the development and integration of models of information, design and fabrication in the new field of landscape architecture and digital fabrication. However, much more needs to be done.

Starting with the survey, real-time feedback on large-scale landscape processes are essential for an informed robotic response. One solution would be the extension of the aerial lidar platform to enable point clouds to stream directly to the design environment and to observe the evolution of large-scale terrain over more extended time periods. This would also allow for an efficient implementation of maintenance strategies. Whereas the distance between the physical landscape and the virtual design environment is considerably smaller due to point cloud technology, on-site visualization and augmentation technologies could significantly improve intuitive design and robotic construction processes. To leverage the full potential of terrain structures and its ecology, more diverse and comprehensive sensing technology like ground-penetrating radar or multispectral image analysis can be applied. This would enable a better understanding and economical use of the heterogeneous make-up and processes in natural granulates. Therefore, the encoding, storing, and retrieving of attributes within the design environment needs more attention.

While Docofossor provides accessibility to custom parametric modelling and computation without any coding skills, the choice for a graphical programming interface comes with disadvantages as well. To explore the full potential of digital native tools, a start has been made to translate Docofossor to an object-oriented terrain modelling library called COMPAS TERRAIN as an extension to the open-source COMPAS framework. This will allow stand-alone implementations of implicit modelling methods and a direct use of existing open-source GIS libraries. Although Docofossor provides a small selection of standard topographic primitives, more flexibility is required in the creation of landforms. Instead of encoding ready-made typologies, the complex and unstructured nature of geomorphic form demands abstraction. Here, a topological understanding can provide a high-level description in the systematisation of three-dimensional form. A better understanding in the structure of topography would therefore be very valuable.

To best situate landscape architecture as the discipline tasked with the organisation our environment, actionable knowledge on the design of ecological systems is needed. Developments in simulating natural processes and their environmental effects within the early design phases would therefore be beneficial. In this dissertation, a start has been made to time-based design approaches using simulation and animation, but more extensive computation and generation tools will be mandatory to conceive the evolution of terrain between natural and robotic forces. Here, artificial intelligence approaches to the simulation of natural processes might make them fast enough for intuitive application in the design phase.

As more autonomous earth-moving equipment will become available, the type and flexibility of robotic manipulation will expand. This research focussed on the capabilities of the converted walking excavator HEAP to enable autonomous navigation and the shaping and finishing of free-form geometry in rough terrain. However, it is not specifically good in hauling of material. To extend robotic formation processes to large-scale landscapes, alternative, multi-robot systems will have to be imagined. As robotic systems are particularly well suited for multipurpose tasks, they might look very different from the specialised equipment with on-board control we see today.

In general, the benefits of adaptive, emergent, and open-ended design and fabrication strategies are facilitated through various forms of computation as it enables the dynamic response to dynamic environments. However, more research has to be done in the relation between designed form and designed ecology to make sense of the unstructured nature of the terrain. As such, a new field of research in computational landscape topology might be well-positioned in developing tools, techniques and processes to empower the next generation of landscape designers.

6.5 Final Reflections

This dissertation presented new terrain modelling tools, dynamic design methods and processes, and robotic fabrication strategies for the construction of earthworks using a topological approach in landscape architecture. These developments are not meant to be a result, but aspires to provide tools and ideas from which novel applications to the organisation of our environment may arise. It showed how research by design drives technology forward, and hopes it may spur more effort towards this research approach in general. This also counts for the collaborative nature of this research, as none of the developments would have been made without the many moments of insight and reflection this provides.

The focus on performance (how things work) may free the landscape from any preconceived idea of what nature should be (how things look like). It acknowledges the value of a renewed craft by working in terrain with digital tools. As the design of natural material is constrained and guided by multiple actors, the degree of control for a designer will be more limited, shifting its role towards a director of processes. However, the fundamental goal for landscape design will always be the organisation of the environment, where landscape topology combined with a new earth-moving grammar may provide the language and tools to find a fitting form as an artistic endeavour.

Now that this project has come to an end, the author is left with a feeling of excitement that he was able to support in however a small way to the evolution of future landscapes. As the dissertation aimed to think and act responsibly on the load-bearing structure of natural material, he hopes that it may once sediment in terrain.

Appendix A

Documentation Docofossor

A.1 Documentation

Docofossor is a collection of landscape modelling components using distance functions. It is a component library for Rhino 3D Grasshopper. It is developed to model cut and fill operations by a robotic excavator in landscape architectural design. It allows a continues transformation of the topography by point, path, area or volume operations on a digital terrain model (DTM). This documentation describes the data structure of Docofossor and provides a reference for the input and output parameters in the component library. It has been developed by Ilmar Hurkxkens and Mathias Bernhard. At the time of writing its version number is 0.904, the current version can be downloaded here: https://www.food4rhino.com/app/docofossor.

A.1.1 Docofossor list format

The Docofossor format is used to calculate Boolean operations within elevation data. Docofossor's data structure is based on a single list that defines a rectangular grid from topographic data. The Docofossor list *df[]* consist of a header part (dimension list) that holds the properties of the grid such as the cell size, the number of rows and columns, and the coordinates of the origin of the grid. The header information is followed by z-values coming from a Digital Terrain Model (in column-major order starting bottom left).

A.1.2 Dimension list

The first 10 values of the *df[]* list holds the following information, specified as the *dim[]* list:

Line	Type	Variable	Description
dim[0]	int	nc	Number of columns.
dim[1]	int	nr	Number of rows.
dim[2]	float	ox	X coordinate of the local origin (lower left corner of the grid, center of the cell).
dim[3]	float	oy	Y coordinate of the local origin (lower left corner of the grid, center of the cell).
dim[4]	float	cx	Cellsize X.
dim[5]	float	cy	Cellsize Y.
dim[6]	-	-	-
dim[7]	-	-	-
dim[8]	float	gx	X coordinate of the global origin (lower left corner of the grid, center of the cell).
dim[9]	float	gy	Y coordinate of the global origin (lower left corner of the grid, center of the cell).

Note: Position 6 and 7 are left free to future-proof the df[] list.

A.1.3 List of z-values

The values after line 10 of the *df[]* list hold the z-values of the digital terrain model, specified as the *lz[]* list.

Line	Type	Description
lz[0]	float	Z-value of the lower left corner of the grid.
lz[1]	float	Next Z-value of the grid in column-major order.
lz[2]	float	Next Z-value of the grid in column-major order.
…		

A.2 Component Library

Docofossor is using the RhinoScriptSyntax in Python to establish a connection to the Rhino geometry and IronPython for the calculations. The components are separated in categories in the Grasshopper toolbar. For now, there are seven categories comprising *I/O*, *Grid*, *Operations Relative*, *Operations Absolute*, *Generative*, *Analysis*, and *Geometry*. They are made available as a set of components for Rhino Grasshopper. Use the list below to navigate to the respective component descriptions.

I/O

The I/O components provide tools for interoperability between DTM's and rhino geometry. At import time, it is possible to filter and shift the location of the grid, so not all the data has to be loaded in case high-resolution maps are not required. It also allows the creation of an empty grid, where all the z-values are set to zero. The export components write files to the grasshopper working directory.

Empty Grid
Creates an empty grid of Z-values and returns the list and the dimensions.

Inputs	nc	Number of columns.
	nr	Number of rows.
	ox	Offset in X.
	oy	Offset in Y.
	cx	Cellsize X.
	cy	Cellsize Y.
Outputs	df	The Docofossor list.

Import ASC
Reads Z-values from a *.ASC-file.

Inputs	f	The filepath to the asc-file.
	n	Number of rows and columns to skip (every n-th r/c).
	sx	Translates the grid to a local X-origin. The original origin is stored and used to restore the grid to global coordinates at export time.
	sy	Translates the grid to a local Y-origin. The original origin is stored and used to restore the grid to global coordinates at export time.
Outputs	df	The Docofossor list.

Import DF

Reads the distance field from a Docofossor data file (*.df).

Inputs	f	The filepath to the df-file.
	n	Number of rows and columns to skip (every n-th r/c).
Outputs	df	The Docofossor list.

Import Points

Creates the Docofossor distance field from points on a regular grid.

Inputs	pts	Points to convert to Docofossor distance field (only orthogonal and regular grid points).
	n	Number of rows and columns to skip (every n-th r/c).
	sx	Translates the grid to a local X-origin. The original origin is stored and used to restore the grid to global coordinates at export time.
	sy	Translates the grid to a local Y-origin. The original origin is stored and used to restore the grid to global coordinates at export time.
Outputs	df	The Docofossor list.

Import XYZ

The *Import XZY* component imports a text file to a *df* list that has topographic data stored as a list of x, y, and z values separated by whitespace characters. Each point should start at a new line.

Inputs	f	The filepath to the xyz-file (it will also take txt files).
	n	Number of rows and columns to skip (every n-th r/c).
	sx	Translates the grid to a local X-origin. The original origin is stored and used to restore the grid to global coordinates at export time.
	sy	Translates the grid to a local Y-origin. The original origin is stored and used to restore the grid to global coordinates at export time.
Outputs	df	The Docofossor list.

Export ASC

Writes a new .asc file of the point locations in global coordinates.

Inputs	df	Docofossor list to work on.
	f	The name of the file.
	w	Use a Boolean button, set True to start writing.

Export DF

Writes a new .df file containing the dimensions and z-values of the docofossor list in global coordinates.

Inputs	df	Docofossor list to work on
	f	The name of the file
	w	Use a Boolean button, set True to start writing

Export XYZ

Writes a new XYZ file of the center cell location in global coordinates.

Inputs	df	Docofossor list to work on.
	f	The name of the file.
	w	Use a Boolean button, set True to start writing.

GRID

The Grid components provide utilities that analyse and operate on the distance fields as a whole. They allow to set global and local coordinates, crop the grid to a specific region and filters or interpolates the elevation data. Additions of two separate grids are also implemented. Finally, it gives information on cut and fill volumes and can extract a difference map between two distance fields. Finally, it gives some general information on the dimensions and location of the elevation data.

Grid Global

Sets the Docofossor grid back to the original global coordinates.

Inputs	df	The Docofossor list to work on.
Outputs	df	The Docofossor list in global coordinates.

Grid Shift

Shifts the Docofossor grid in local coordinates. If left blank the grid origin will be set to x=0 and y=0. The original origin is stored and used to restore the grid to global coordinates at export time.

Inputs	df	The Docofossor list to work on.
	sx	Shift the origin of the grid in X direction.
	sy	Shift the origin of the grid in Y direction.
Outputs	df	The Docofossor list with the new origin.

Grid Compare

Compares two terrains (lists of Z-values) with each other and provide cubature for cut, fill and balance.

Inputs	df	The first Docofossor list.
	df2	The second Docofossor list to compare with.
Outputs	cut	The volume added from df1 to df2.
	fill	The volume added from df1 to df2.
	balance	The volume difference.
	df	Docofossor list with difference values (distance field of the volume delta).

Grid Info

Outputs grid information data like location, number of cells, resolution and minimum and maximum elevation for reference.

Inputs	df	The Docofossor list.
Outputs	info	Grid information data.

Grid Addition

Adds two Docofossor distance fields together.

Inputs	df	The original Docofossor list.
	df_add	The Docofossor list to add.
Outputs	df	The Docofossor list.

Grid Filter

Filters a list of Z-values to include only every n-th row and/or column.

Inputs	df	The Docofossor list to work on.
	n	Number of rows and columns to skip (every n-th r/c).
Outputs	df	The Docofossor list.

Grid Interpolation

Increases the resolution of the Docofossor distance field by 2, using linear interpolation.

Inputs	df	The Docofossor list to work on.
Outputs	df	The Docofossor list in 2x resolution.

Grid Region

Crops the grid to a curve (bounding box), for faster operation.

Inputs	df	The Docofossor list to work on.
	crv	The closed curve to crop the grid.
Outputs	df	The Docofossor list.

Grid Smooth

Smoothen a terrain model by applying a 2D Gaussian convolution kernel.

Inputs	df	The Docofossor list to work on.
	rad	The radius of the kernel (5 if not specified).
Outputs	df	The Docofossor list.

RELATIVE OPERATIONS

The relative operations provide tools for cut and fill on points, paths and areas. They provide parameters for the slope angle, as well as the width and maximum height/depth of the operation. Each component also outputs the volume difference (negative value for excavation, positive for deposition).

Cut On Point

Creates a cut on a point and blends it into the terrain.

Inputs	df	The Docofossor list to work on.
	pt	Excavation location (point3D).
	mxd	Maximum depth.
	sa	Slope angle (default = 33 degrees).
	method	Boolean toggle between relative- and blended deposition.
Outputs	df	The Docofossor list.
	vol	The volume delta.

Fill On Point

Creates a fill on a point and blends it into the terrain.

Inputs	df	The Docofossor list to work on.
	pt	Fill location (point3D).
	mxh	Maximum height.
	sa	Slope angle (default = 33 degrees).
Outputs	df	The Docofossor list.
	vol	The volume delta.

Cut On Path

Creates a relative cut along a path curve.

Inputs	df	The Docofossor list to work on.
	crv	The path curve.
	mxd	Maximum depth at the center.
	w	Width at the top of the cutting tool.
	sa	Slope angle (default = 33 degrees).
Outputs	df	The Docofossor list.
	vol	The volume delta.

Fill On Path

Creates a relative fill along a path curve.

Inputs	df	The Docofossor list to work on.
	crv	The path curve.
	mxh	Maximum height at the center.
	w	Width at the bottom of the cutting tool.
	sa	Slope angle (default = 33 degrees).
Outputs	df	The Docofossor list.
	vol	The volume delta.

Cut On Area

Creates a relative cut within a boundary curve.

Inputs	df	The Docofossor list to work on.
	crv	The boundary curve.
	mxd	Maximum depth.
	sa	Slope angle (default = 33 degrees).
Outputs	df	The Docofossor list.
	vol	The volume delta.

Fill On Area

Creates a relative fill within a boundary curve.

Inputs	df	The Docofossor list to work on.
	crv	The boundary curve.
	mxh	Maximum height.
	sa	Slope angle (default = 33 degrees).
Outputs	df	The Docofossor list.
	vol	The volume delta.

ABSOLUTE OPERATIONS

The absolute operations provide tools for cut and fill on points, paths and surfaces. They provide parameters for the slope angle, as well as the width and maximum height/depth of the operation. Each component also outputs the volume difference (negative value for excavation, positive for deposition).

Cut In Point

Creates an absolute cut in a point.

Inputs	df	The Docofossor list to work on.
	pt	Excavation location (point3D).
	sa	Slope angle (default = 33 degrees).
	d	Maximum cut distance from the point (default = 10).
Outputs	df	The Docofossor list.
	vol	The volume delta.

Fill In Point

Creates an absolute deposition in a point.

Inputs	df	The Docofossor list to work on.
	pt	Fill location (point3D).
	sa	Slope angle (default = 33 degrees).
	d	Maximum fill distance from the point (default = 10).
Outputs	df	The Docofossor list.
	vol	The volume delta.

Cut and Fill In Path

Creates a trapezoidal cut and fill along path curves. Where the curve sits below the exiting terrain a cut will be made, while a fill will be made when the curve sits above the terrain.

Inputs	df	The Docofossor list to work on.
	crv	One or multiple path curves.
	sa	Slope angle (default = 33 degrees).
	w	Width at the bottom/top of the cut/fill tool.
	d	Maximum cutting distance from the curve (default = 30).
Outputs	df	The Docofossor list.
	vol	The balanced volume delta.

Cut In Path

Creates a trapezoidal cut along path curves.

Inputs	df	The Docofossor list to work on.
	crv	One or multiple path curves.
	wb	Width at the bottom of the carving tool.
	sa	Slope angle (default = 33 degrees).
	d	Maximum cutting distance from the curve (default = 30).
Outputs	df	The Docofossor list.
	vol	The volume delta.

Fill In Path

Creates a trapezoidal fill along path curves.

Inputs	df	The Docofossor list to work on.
	crv	One or multiple path curves.
	wt	Width at the top of the carving tool.
	sa	Slope angle (default = 33 degrees).
	d	Maximum cutting distance from the curve (default = 30).
Outputs	df	The Docofossor list.
	vol	The volume delta.

Cut and Fill In Surface

Fits the landscape to a given surface by pulling the points (both cut and fill) and connects it to the surrounding terrain using a slope.

Inputs	df	The Docofossor list to work on.
	srf	The surface to drag the points to.
	sa	Slope angle (default = 33 degrees).
	d	Maximum cutting distance from the surface (default = 30).
Outputs	df	The Docofossor list.
	vol	The balanced volume delta.

Cut In Surface

Fits the landscape to a given surface by pulling the points (cut) and connects it to the surrounding terrain using a slope.

Inputs	df	The Docofossor list to work on.
	srf	The surface to drag the points to.
	sa	Slope angle (default = 33 degrees).
	d	Maximum cutting distance from the surface (default = 30).
Outputs	df	The Docofossor list.
	vol	The volume delta.

Fill In Surface

Fits the landscape to a given surface by pulling the points (fill) and connects it to the surrounding terrain using a slope.

Inputs	df	The Docofossor list to work on.
	srf	The surface to drag the points to.
	sa	Slope angle (default = 33 degrees).
	d	Maximum cutting distance from the surface (default = 30).
Outputs	df	The Docofossor list.
	vol	The volume delta.

GENERATIVE

The generative components provide tools for adding noise or a waveform pattern relative to the terrain. They provide parameters for wavelength and amplitude, as well as a curve input to specify a specific region and a smoothing distance to blend back into the terrain.

Noise

Relative displacement using Perlin Noise.

Inputs	df	The Docofossor list to work on.
	crv	A list of closed curves as boundary region.
	wl	The wavelength (Default = 16).
	a	The amplitude (Default = 4).
	s	The smoothing distance from the curve (Default = 8).
Outputs	df	The Docofossor list.

Sinewave

Relative displacement using a sine wave.

Inputs	df	The Docofossor list to work on.
	crv	A list of closed curves as boundary region.
	wl	The wavelength (Default = 16).
	a	The amplitude (Default = 4).
	s	The smoothing distance from the curve (Default = 8).
Outputs	df	The Docofossor list.

ANALYSIS

The analysis components provide tools to extract various cell properties like slope vector and orientation. They operate on the whole grid, and the output is a list that corresponds to the elevation data of the Docofossor list.

Slope Vector

Calculates the gradient direction vectors of every elevation point.

Inputs	df	The Docofossor list to work on.
Outputs	a	List of gradient vectors, magnitude corresponding to slope.

Viewshed

Analyses the visibility of the terrain (3d viewshed) from a given start point..

Inputs	df	The Docofossor list to work on.
	pt	The position of the viewer to be analysed.
	h	Height of the eye above ground (default = 1.6).
Outputs	a	List of gradient vectors, magnitude corresponding to slope.
	va	List of visibilities (Boolean) for each point.
	spt	Point object indicating the actual position used for calculation.

Shortest Path

Calculates the shortest path between two points.

Inputs	df	The Docofossor list to work on.
	omap	List of obstacles, 1 is free, 0 is occupied.
	sp	The starting point.
	tp	The target point.
	c	Type of neighbourhood, allowed moves. 1 > 4 neighbors sharing an edge. 2 > 8 neighbors sharing a vertex.
	f	factor to multiply height difference (0=no influence).
Outputs	dst	Distance travelled.
	pl	polyline of the route (in 2D).

GEOMETRY

The geometry components provide tools for creating Rhino geometry from the Docofossor list. At the moment, components are available for meshes and points.

Grid Mesh

Creates a mesh of quads on the point grid.

Inputs	df	The Docofossor list to work on.
Outputs	m	The new mesh.

Grid Points

Creates points from the z values and grid dimensions in the Docofossor list.

Inputs	df	The Docofossor list to work on.
Outputs	m	The Point list (x,y,z).

List of Figures

References

[1] Robert Smithson. "A Sedimentation of the Mind: Earth Proposals". In: *Artforum* 7.1 (Sept. 1968).

[2] Jane Hutton. "Substance and Structure I: The Material Culture of Landscape Architecture". In: *Harvard Design Magazine* 36. Landscape Architecture's Core? (2013).

[3] Kenneth Frampton. "Towards a Critical Regionalism: Six Points for an Architecture of Resistance". In: *The Anti-Aesthetic: Essays on Postmodern Culture*. Ed. by Hal Foster. Port Townsend: Bay Press, 1983, pp. 16–31.

[4] Christophe Girot. *The Course of Landscape Architecture*. New York, NY: Thames & Hudson, 2016.

[5] Roland Fuchs, Mary Conran, and Elizabeth Louis. "Climate Change and Asia's Coastal Urban Cities: Can They Meet the Challenge?" In: *Environment and Urbanization ASIA* 2.1 (Mar. 2011), pp. 13–28. DOI: 10.1177/097542531000200103.

[6] Günter Blöschl et al. "Changing Climate Shifts Timing of European Floods". In: *Science* 357.6351 (Aug. 11, 2017), pp. 588–590. DOI: 10.1126/science.aan2506.

[7] George Bull. "Ridge and Furrow". In: *Landscape. Journal of the Landcape Institute* Landscape Spring (2014). URL: http://www.landscapethejournal.org/Ridge-and-furrow.

[8] Charles Waldheim. "Landscape as Urbanism". In: *The Landscape Urbanism Reader*. Ed. by Charles Waldheim. New York: Princeton Architectural Press, 2006.

[9] Pierre Bélanger. *Landscape as Infrastructure: A Base Primer*. Abingdon, Oxon ; New York, NY: Routledge, 2017.

[10] Charles Waldheim. "Landscape as Architecture". In: *Harvard Design Magazine* Landscape Architecture's Core?36 (2013), pp. 116–123.

[11] Christophe Girot et al., eds. *Topologie - Topology*. 2., überarb. und neu übers. Aufl. Pamphlet / Institure of Landscape Architecture 15. Zürich: Gta-Verlag, 2013.

[12] Dominic Jud et al. "Planning and Control for Autonomous Excavation". In: *IEEE Robotics and Automation Letters* 2.4 (Oct. 2017), pp. 2151–2158. DOI: 10.1109/LRA.2017.2721551.

[13] Fabio Gramazio, Matthias Kohler, and Jan Willmann, eds. *The Robotic Touch: How Robots Change Architecture*. Zurich: Park Books, 2014.

[14] William Brian Arthur. *The Nature of Technology: What It Is and How It Evolves*. 1. Free Press pbk. ed. New York: Free Press, 2011.

[15] Taeke de Jong and Teo van der Voordt, eds. *Ways to Study and Research: Urban, Architectural, and Technical Design*. Delft: DUP Science, 2005.

[16] Clive Dilnot. "The Science of Uncertainty: The Potential Contribution of Design to Knowledge". In: *Proceedings of the Doctoral Education in Design Conference*. Ohio State University, 1998.

[17] James Melsom. "The Apparatus of the Invisble Landscape: Sensing beyond Sight." In: *Field Instruments of Design*. Ed. by Ilmar Hurkxkens and Christophe Girot. Pamphlet 19. Zurich: gta Verlag, 2015.

[18] Gye-Chun Cho, Jake Dodds, and Carlos Santamarina. "Particle Shape Effects on Packing Density, Stiffness, and Strength: Natural and Crushed Sands". In: *Journal of Geotechnical and Geoenvironmental Engineering* 132.5 (May 2006), pp. 591–602. DOI: 10.1061/(ASCE)1090-0241(2006)132:5(591).

[19] Christopher Alexander. *Notes on the Synthesis of Form*. 17. printing. Cambridge, Mass.: Harvard Univ. Press, 1964.

[20] Kenneth Frampton. "Rappel à ;Órde, the Case for the Tectonic". In: *Theorizing a New Agenda for Architecture: An Anthology of Architectural Theory, 1965-1995*. Ed. by Kate Nesbitt. 1st ed. New York: Princeton Architectural Press, 1996.

[21] Lewis Mumford. *The City in History: Its Origins, Its Transformations, and Its Prospects*. A Harvest Book. San Diego New York London: Harcourt, Inc, 1989.

[22] Vittorio Gregotti. "Territory and Architecture". In: *Architectural Design Profile* 59.5-6 (1985), pp. 28–34.

[23] Kenneth Frampton. *Studies in Tectonic Culture: The Poetics of Construction in Nineteenth and Twentieth Century Architecture*. Ed. by John Cava. Cambridge, Mass: MIT Press, 1995.

[24] Sanford Kwinter. “Landscapes of Change: Boccioni’s "Stati d’animo" as a General Theory of Models”. In: *Assemblage* 19 (1992), pp. 50–65. DOI: 10.2307/3171176. JSTOR: 3171176.

[25] Eugène-Emmanual Viollet-le-Duc. *Mont Blanc: A Treatise on Its Geodisical and Geological Constitution; Its Transformations; and the Ancient and Recent State of Its Glaciers*. London: Gilbert and Rivington, 1877.

[26] Conrad H. Waddington. *The Strategy of the Genes*. Bristol: Arrowsmith Ltd, 1957.

[27] Harlow C. Landphair and John L. Motloch. *Site Reconnaissance and Engineering: An Introduction for Architects, Landscape Architects, and Planners*. New York: Elsevier, 1985.

[28] Caroline Westort. “Designing Digital Topography: Opportunities for Greater Efficiency with a Primitives and Operators Approach”. In: (2015).

[29] Marzieh Mokarram and Dinesh Sathyamoorthy. “A Review of Landform Classification Methods”. In: *Spatial Information Research* 26.6 (Dec. 2018), pp. 647–660. DOI: 10.1007/s41324-018-0209-8.

[30] Peter A. Shary, Larisa S. Sharaya, and Andrey V. Mitsusov. “The Problem Of Scale-Specific And Scale-Free Approaches In Geomorphometry”. In: *Geografia Fisica e Dinamica Quaternaria* 28 (2005), pp. 81–101.

[31] William R. Morrish. *Civilizing Terrains: Mountains, Mounds and Mesas*. Rev. 2nd ed. Architectural Documents 1. San Francisco, CA: William Stout Publishers, 1996.

[32] Caroline Westort. “Methods for Sculpting Digital Topographic Surfaces”. PhD Thesis. Zurich: ETH, 1998.

[33] Steven Strom, Kurt Nathan, and Jake Woland. *Site Engineering for Landscape Architects*. Sixth edition. Hoboken, New Jersey: Wiley, 2013.

[34] Tim Ingold. “The Textility of Making”. In: *Cambridge Journal of Economics* 34.1 (Jan. 1, 2010), pp. 91–102. DOI: 10.1093/cje/bep042.

[35] Piere Bélanger. “Landscape Infrastructure: Urbanism Beyond Engineering”. PhD Thesis. Wageningen: Wageningen University, 2013.

[36] Ralph Straumann. “Extraction And Characterisation Of Landforms From Digital Elevation Models: Fiat Parsing The Elevation Field”. Zurich: University of Zurich, 2010.

[37] Robert Schmitt et al. *Moving the Earth: Excavation Equipment, Methods, Safety, and Cost*. Seventh Edition. New York, NY: McGraw-Hill Education, 2018.

[38] William Hogarth and Ronald Paulson. *The Analysis of Beauty*. New Haven, Conn: Published for the Paul Mellon Centre for Britsh Art by Yale University Press, 1997 (originally published in 1753).

[39] Heinrich M. Jaeger, Sidney R. Nagel, and Robert P. Behringer. "The Physics of Granular Materials". In: *Physics Today* 49.4 (Apr. 1996), pp. 32–38. DOI: 10.1063/1.881494.

[40] Eduard Imhof. *Kartographische Geländedarstellung*. Berlin: De Gruyter, 1965.

[41] Christophe Girot. "The Elegance of Topology". In: *Topology - Topical Thoughts on the Contemporary Landscape*. Landscript 3 (2013). Ed. by Christophe Girot et al.

[42] Philip A. Allen. "Time Scales of Tectonic Landscapes and Their Sediment Routing Systems". In: *Geological Society, London, Special Publications* 296.1 (2008), pp. 7–28. DOI: 10.1144/SP296.2.

[43] Jianguo Wu and Orie L. Loucks. "From Balance of Nature to Hierarchical Patch Dynamics: A Paradigm Shift in Ecology". In: *The Quarterly Review of Biology* 70.4 (Dec. 1995), pp. 439–466. DOI: 10.1086/419172.

[44] Robert Pyke. *On the Limitations of Limit Equilibrium Analyses of Slope Stability*. June 6, 2017. URL: https://www.linkedin.com/pulse/limitations-limit-equilibrium-analyses-slope-stability-robert-pyke (visited on 05/17/2020).

[45] Roxi Thoren. *Landscapes of Change: Innovative Designs and Reinvented Sites*. First edition. Portland, Oregon: Timber Press, Inc, 2014.

[46] George Mathias Kondolf. "Geomorphic and Environmental Effects of In-stream Gravel Mining". In: *Landscape and Urban Planning* 28.2-3 (Apr. 1994), pp. 225–243. DOI: 10.1016/0169-2046(94)90010-8.

[47] Peter M. Vitousek et al. "Human Domination of Earth's Ecosystems". In: *Science* 277.5325 (1997), pp. 494–499. DOI: 10.1126/science.277.5325.494.

[48] Jennifer Foster and Heidi Schopf. "Mineral Migration: Extracting, Recomposing, Demolishing, and Recolonizing Toronto's Landscape". In: *Material Culture: Assembling and Disassembling Landscapes*. Ed. by Jane Hutton. Landscript 5. Berlin: Jovis, 2017.

[49] Christophe Girot et al. "Scales of Topology in Landscape Architecture". In: *Scales of the Earth*. Ed. by Gareth Doherty, El Hadi Jazairy, and Harvard University. New Geographies 4. Cambridge, Mass: Harvard Univ. Press, 2011.

[50] Paul J. Crutzen and Eugene F. Stoermer. "The 'Anthropocene'". In: *Global Change Newsletter* (2000).

[51] Jane Hutton. "Material as Method". In: *Material Culture: Assembling and Disassembling Landscapes*. Ed. by Jane Hutton. Landscript 5. Berlin: Jovis, 2017.

[52] *Ceneri Base Tunnel*. URL: https://www.alptransit.ch/en/ceneri/ceneri/ (visited on 04/03/2020).

[53] Marinke Steenhuis and Fransje Hooimeijer, eds. *Maakbaar Landschap: Nederlandse Landschapsarchitectuur, 1945-1970*. Rotterdam: NAi Uitgevers, 2009.

[54] Mohsen Mostafavi and Gareth Doherty, eds. *Ecological Urbanism*. Zürich: Lars Müller Publishers, 2016.

[55] Georges Descombes, ed. *Aire: the river and its double = La riviere et son double = Der Fluss und sein Doppelgänger*. Zurich: Superpositions and Park Books AG, 2018.

[56] *Renaturation of the River Aire*. URL: http://landezine.com/index.php/2016/06/renaturation-of-the-river-aire-geneva/ (visited on 05/06/2020).

[57] Rod Barnett. *Emergence in Landscape Architecture*. London ; New York: Routledge, 2013.

[58] Antoine Picon. "Substance and Structure II : The Digital Culture of Landscape Architecture." In: *Harvard Design Magazine* Landscape Architecture's Core?36 (2013).

[59] Rod Barnett. *The Ten Point Guides to Emergence*. 2013. URL: http://www.nonlinearlandscapes.com/the-ten-point-guides-to-emergence (visited on 05/18/2020).

[60] Pascal Hersen. "Flow Effects on the Morphology and Dynamics of Aeolian and Subaqueous Barchan Dunes: SUBAQUEOUS BARCHANS". In: *Journal of Geophysical Research: Earth Surface* 110.F4 (Dec. 2005), n/a–n/a. DOI: 10.1029/2004JF000185.

[61] *Sediment Transportation and Sorting*. URL: https://www.northstonematerials.com/basic_geological_classification (visited on 04/02/2019).

[62] David R. Montgomery. *Dirt: The Erosion of Civilizations*. Berkeley: Univ. of California Press, 2012.

[63] Robert E. White. *Principles and Practice of Soil Science: The Soil as a Natural Resource*. 4th ed. Malden, MA: Blackwell Pub, 2006.

[64] Henry Lin. "Three Principles of Soil Change and Pedogenesis in Time and Space". In: *Soil Science Society of America Journal* 75.6 (Nov. 2011), pp. 2049–2070. DOI: 10.2136/sssaj2011.0130.

[65] Paul Voroney. "The Soil Habitat". In: *Soil Microbiology, Ecology and Biochemistry*. Elsevier, 2007, pp. 25–49. DOI: 10.1016/B978-0-08-047514-1.50006-8.

[66] Budiman Minasny and Alex B. McBratney. "Mechanistic Soil–Landscape Modelling as an Approach to Developing Pedogenetic Classifications". In: *Geoderma* 133.1-2 (July 2006), pp. 138–149. DOI: 10.1016/j.geoderma.2006.03.042.

[67] Moses Tenywa, Julius Zake, and Rattan Lal. “Building upon Traditional Knowledge to Enhance Resilience of Soils in Sub-Saharan Africa”. In: *Principles of Sustainable Soil Management in Agroecosystems*. Boca Raton, Fla.: CRC Press, 2013, pp. 110–134. URL: http://www.crcnetbase.com/isbn/9781466513471.

[68] Joseph Claghorn. “Algorithmic Landscapes. Computational Methods for the Mediation of Form, Information, and Performance in Landscape Architecture”. Hannover: Gottfried Wilhelm Leibniz Universität, 2018.

[69] Lucian Drăguţ and Clemens Eisank. “Object Representations at Multiple Scales from Digital Elevation Models”. In: *Geomorphology* 129.3-4 (June 2011), pp. 183–189. DOI: 10.1016/j.geomorph.2011.03.003.

[70] *OSHA Technical Manual Section V: Chapter 2 - Excavations: Hazard Recognition in Trenching and Shoring*. URL: https://www.osha.gov/dts/osta/otm/otm_v/otm_v_2.html (visited on 07/16/2019).

[71] Ammar Mirjan. “Aerial Construction. Robotic Fabrication of Tensile Structures with Flying Machines”. PhD Thesis. ETH Zurich, 2016.

[72] Ben Popper. “Robo-Bulldozers Guided by Drones Are Helping Japan’s Labor Shortage”. In: *The Verge* (Oct. 13, 2015). URL: https://www.theverge.com/2015/10/13/9521453/skycatch-komatsu-drones-construction-autonomous-vehicles (visited on 04/03/2020).

[73] *Quadrant of Snellius*. 1610–1620. URL: http://mmb-web.adlibhosting.com/ais54/Details/collect/19012 (visited on 04/08/2020).

[74] Eelco Hooftman. “Another Green World”. In: *Landscape Vision Motion: Visual Thinking in Landscape Culture*. Ed. by Christophe Girot and Fred Truniger. Landscript 1. Berlin: Jovis, 2012.

[75] Ervine Lin. “Point Clouds as a Representative and Performative Format for Landscape Architecture”. PhD Thesis. ETH Zurich, Department of Architecture, 2016.

[76] Jörg Rekittke. “Mandatory Fieldwork”. In: *Field Instruments of Design*. Ed. by Ilmar Hurkxkens and Christophe Girot. Pamphlet 19. Zurich: gta Verlag, 2015.

[77] Ilmar Hurkxkens. “Instruments of Design: On Surveying and Designing Site-Specifitc Material”. In: *Field Instruments of Design*. Ed. by Christophe Girot and Ilmar Hurkxkens. Pamphlet 19. Zurich: gta Verlag, 2015, pp. 23–33.

[78] Christophe Girot. “A Return to Terrain”. In: *Field Instruments of Design*. Ed. by Ilmar Hurkxkens and Christophe Girot. Pamphlet 19. Zurich: gta Verlag, 2015.

[79] Charles Waldheim. “Provisional Notes on Landscape Representation and Digital Media”. In: *Landscape Vision Motion: Visual Thinking in Landscape Culture*. Ed. by Christophe Girot and Fred Truniger. Landscript 1. Berlin: Jovis, 2012.

[80] Roger Tomlinson. “Computer Matting: An Introduction to the Use of Electronic Computers in the Storage, Compilation and Assessment of Natural and Economic Data for the Evaluation of Marginal Lands”. In: *Report*. National Land Capability Inventory Seminar. Ottowa, 1962.

[81] Ian L. McHarg. *Design with Nature*. 25th anniversary ed. New York Chichester Brisbane Toronto Singapore: John Wiley & Sons, Inc, 1969.

[82] Mathias Bernhard, Michael Hansmeyer, and Benjamin Dillenburger. “Volumetric Modelling for 3D Printed Architecture”. In: *AAG 2018, Advances in Architectural Geometry 2018*. Ed. by Lars Hesselgren et al. Klein Publishing GmbH, 2018, pp. 392–415.

[83] Kristijan Ljutić and Sergije Babić. “Digital Terrain Model Application in Road Planning and Design”. In: *International Conference on Road and Rail Infrastructure*. CETRA. Opatija, 2010.

[84] Kathryn Gustafson. “Land Movement”. In: *Thinking the Contemporary Landscape*. Ed. by Christophe Girot and Dora Imhof. First edition. New York: Princeton Architectural Press, 2017.

[85] *The Touch Haptic Device*. URL: https://www.3dsystems.com/haptics-devices/touch (visited on 05/20/2020).

[86] Hiroshi Ishii. “The Tangible User Interface and Its Evolution”. In: *Communications of the ACM* 51.6 (June 2008), pp. 32–36. DOI: 10.1145/1349026.1349034.

[87] Ilmar Hurkxkens and Georg Munkel. “Speculative Precision: Combining Haptic Terrain Modelling with Real-Time Digital Analysis for Landscape Design”. In: *Peer Reviewed Proceedings of Digital Landscape Architecture 2014 at the ETH Zurich*. Wichmann, 2014, pp. 399–405.

[88] Ingeborg Rocker. “Calculus-Based Form: An Interview with Greg Lynn”. In: *Architectural Design* 76.4 (July 2006), pp. 88–95. DOI: 10.1002/ad.298.

[89] Bob Sheil, ed. *Manufacturing the Bespoke: Making and Prototyping Architecture*. AD Reader. Chichester: Wiley, 2012.

[90] Arturo Tedeschi. *AAD - Algorithms-Aided Design: Parametric Strategies Using Grasshopper*. First edition. Brienza: Le Penseur publisher, 2014.

[91] Malcolm McCullough. *Abstracting Craft: The Practiced Digital Hand*. 1. paperback ed. Campridge, Mass.: MIT Press, 1998.

[92] Bradley Cantrell and Adam Mekies. “Coding Landscape”. In: *Codify: Parametric and Computational Design in Landscape Architecture*. Ed. by Bradley Cantrell and Adam Mekies. 1st ed. New York, NY : Routledge, 2018.: Routledge, May 1, 2018. DOI: 10.4324/9781315647791.

[93] Axel Kilian. “Design Exploration through Bidirectional Modeling of Constraints”. PhD Thesis. MIT, 2006.

[94] Douglas D. Gransberg, Calin Popescu, and Richard C. Ryan. *Construction Equipment Management for Engineers, Estimators, and Owners*. Civil and Environmental Engineering 21. Boca Raton, FL: CRC Taylor & Francis, 2006.

[95] Kathrin Dörfler. “Strategies for Robotic In Situ Fabrication”. PhD Thesis. ETH Zurich, 2018.

[96] Peter Petschek. *Grading: landscapingSMART, 3D Machine Control Systems, Stormwater Management*. In collab. with Hochschule für Technik Rapperswil. 2nd edition, revised and expanded. Basel: Birkhäuser, 2014.

[97] Jillian Walliss and Heike Rahmann. *Landscape Architecture and Digital Technologies: Re-Conceptualising Design and Making*. Abingdon, Oxon; New York: Routledge, 2016.

[98] *Build Robotics*. 2020. URL: https://www.builtrobotics.com/ (visited on 04/06/2020).

[99] Daniel Schmidt, Martin Proetzsch, and Karsten Berns. “Simulation and Control of an Autonomous Bucket Excavator for Landscaping Tasks”. In: *2010 IEEE International Conference on Robotics and Automation*. 2010 IEEE International Conference on Robotics and Automation (ICRA 2010). Anchorage, AK: IEEE, May 2010, pp. 5108–5113. DOI: 10.1109/ROBOT.2010.5509546.

[100] David A. Bradley and Derek W. Seward. “The Development, Control and Operation of an Autonomous Robotic Excavator”. In: *Journal of Intelligent and Robotic Systems* 21.1 (1998), pp. 73–97. DOI: 10.1023/A:1007932011161.

[101] Ji Zhang and Sanjiv Singh. “LOAM: Lidar Odometry and Mapping in Real-Time”. In: *Robotics: Science and Systems X*. Robotics: Science and Systems 2014. Robotics: Science and Systems Foundation, July 12, 2014. DOI: 10.15607/RSS.2014.X.007.

[102] Olga Luengo, Sanjiv Singh, and Howard Cannon. “Modeling and Identification of Soil-Tool Interaction in Automated Excavation”. In: *Proceedings. 1998 IEEE/RSJ International Conference on Intelligent Robots and Systems. Innovations in Theory, Practice and Applications (Cat. No.98CH36190)*. Proceedings. 1998 IEEE/RSJ International Conference on Intelligent Robots and Systems. Innovations in Theory, Practice and Applications. Vol. 3. Victoria, BC, Canada: IEEE, 1998, pp. 1900–1906. DOI: 10.1109/IROS.1998.724873.

[103] Marco Hutter et al. "Force Control for Active Chassis Balancing". In: *IEEE/ ASME Transactions on Mechatronics* 22.2 (Apr. 2017), pp. 613–622. doi: 10.1109/TMECH.2016.2612722.

[104] Fabio Gramazio, Matthias Kohler, and Michael Hanak, eds. *Digital Materiality in Architecture: Gramazio & Kohler*. Baden: Müller, 2008.

[105] Alvin Huang. "Objects: Technology, Technique, Techné: Creation vs. Contingency in Computational Design". In: *Instabilities and Potentialities*. Ed. by Chandler Ahrens and Aaron Sprecher. 1st ed. New York : Routledge, 2019.: Routledge, Feb. 22, 2019, pp. 125–135. doi: 10.4324/9780429506338-23.

[106] Antoine Picon. "Digital Fabrication, Between Disruption and Nostalgia". In: *Instabilities and Potentialities*. Ed. by Chandler Ahrens and Aaron Sprecher. 1st ed. New York : Routledge, 2019.: Routledge, Feb. 22, 2019, pp. 223–238. doi: 10.4324/9780429506338-23.

[107] Karola Dierichs and Achim Menges. "Material Computation in Architectural Aggregate Systems". In: *Formation, Proceedings of the 30th Annual Conference of the Association for Computer Aided Design In Architecture (ACADIA)*. ACADIA. New York City, 2010, pp. 372–378.

[108] Neri Oxman. "Material Computation". In: *Manufacturing the Bespoke: Making and Prototyping Architecture*. Ed. by Bob Sheil. AD Reader. Chichester: Wiley, 2012, p. 280.

[109] Werkbund Bayern and Museum Villa Stuck, eds. *Frei Otto, Bodo Rasch: Finding Form: Towards an Architecture of the Minimal: The Werkbund Shows Frei Otto, Frei Otto Shows Bodo Rasch: Exhibition in the Villa Stuck, Munich, on the Occasion of the Award of the 1992 Deutscher Werkbund Bayern Prize to Frei Otto and Bodo Rasch*. Stuttgart: Axel Menges, 1995.

[110] Fabio Gramazio, Matthias Kohler, and Jan Willmann. "Thriving Digital Materiality". In: *The Robotic Touch: How Robots Change Architecture*. Zurich: Park Books, 2014.

[111] *Procedural Landscapes*. 2011. url: https://gramaziokohler.arch.ethz.ch/web/d/lehre/208.html (visited on 02/27/2020).

[112] Karen Lee Bar-Sinai, Tom Shaked, and Aaron Sprecher. "Informing Grounds: A Theoretical Framework and Iterative Process for Robotic Groundscaping of Remote Sites". In: *Proceedings of the 39th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*. ACADIA 19: Ubiquity and Autonomy. Austin, Texas, 2019, pp. 258–265.

[113] Leif Estrada. "Towards Sentience". In: *Codify: Parametric and Computational Design in Landscape Architecture*. Ed. by Bradley Cantrell and Adam Mekies. 1st ed. Milton Park, Abingdon, Oxon ; New York, NY : Routledge, 2018.: Routledge, May 1, 2018. doi: 10.4324/9781315647791.

[114] Eugène-Emmanual Viollet-le-Duc. *Rhombohedral System of the Mont Blanc*. Undated. URL: https://www.photo.rmn.fr/archive/10-529598-2C6NU0Y%20RQHFD.html (visited on 03/03/2020).

[115] Henri Eisenbeiss. "UAV Photogrammetry". ETH Zurich, 2009. DOI: 10.3929/ETHZ-A-005939264.

[116] Zhilin Li, Qing Zhu, and Chris Gold. *Digital Terrain Modeling: Principles and Methodology*. New York: CRC Press, 2005.

[117] Péter Fankhauser and Marco Hutter. "A Universal Grid Map Library: Implementation and Use Case for Rough Terrain Navigation". In: *Robot Operating System (ROS) – The Complete Reference*. Ed. by Anis Koubaa. Vol. 625. Volume 1. Springer International Publishing, 2016, pp. 99–120. DOI: 10.1007/978-3-319-26054-9_5.

[118] Ilmar Hurkxkens and Mathias Bernhard. "Computational Terrain Modeling with Distance Functions for Large Scale Landscape Design". In: *Journal of Digital Landscape Architecture*. Berlin: Wichmann Verlag, 2019. URL: http://gispoint.de/fileadmin/user_upload/paper_gis_open/DLA_2019/537663024.pdf (visited on 07/06/2019).

[119] Christophe Girot et al. "The Impossible View of the Saint Gotthard: Surveying, Modeling and Visualizing Alpine Landscapes". In: *Der Gotthard: Landscape - Myths - Technology*. Zurich: Verlag Scheidegger & Spiess, 2016.

[120] *What Are NURBS?* Apr. 8, 2020. URL: https://www.rhino3d.com/nurbs (visited on 04/08/2020).

[121] Jules Bloomenthal and Chandrajit Bajaj, eds. *Introduction to Implicit Surfaces*. The Morgan Kaufmann Series in Computer Graphics and Geometric Modeling. San Francisco, C.A: Morgan Kaufmann Publishers, Inc, 1997.

[122] Mathias Bernhard. "Domain Transforms in Architecture". PhD Thesis. ETH Zurich, 2019. URL: https://doi.org/10.3929/ethz-b-000381227.

[123] Stan Allen. "Field Conditions". In: *Points + Lines: Diagrams and Projects for the City*. 1st ed. New York: Princeton Architectural Press, 1999.

[124] Stephen Ervin and Caroline Westort. "Procedural Terrain: A Virtual Bulldozer". In: *CAAD futures Digital Proceedings* (1995).

[125] Vito Acconci. *Digging Piece*. 1970.

[126] Dominic Jud et al. "Autonomous Free-Form Trenching Using a Walking Excavator". In: *IEEE Robotics and Automation Letters* 4.4 (Oct. 2019), pp. 3208–3215. DOI: 10.1109/LRA.2019.2925758.

[127] Ilmar Hurkxkens et al. "Robotic Landscapes: Designing Formation Processes for Large Scale Autonomous Earth Moving". In: *Impact: Design With All Senses*. Ed. by Christoph Gengnagel et al. Cham: Springer International Publishing, 2019, pp. 69–81. DOI: 10.1007/978-3-030-29829-6_6.

[128] Mateus Van Stralen. "Dynamic Architectural Systems. Parametric Design and Digital Fabrication towards Conversational Customization". Belo Horizonte: Federal Universtity of Mina Gerais, 2017.

[129] Mario Carpo. *The Second Digital Turn: Design beyond Intelligence*. Writing Architecture. Cambridge, Massachusetts: The MIT Press, 2017.

[130] *ISO 14688-1:2017 Identification and Classification of Soil*. Apr. 6, 2020. URL: https://www.iso.org/standard/66345.html (visited on 04/06/2020).

[131] Fadri Furrer et al. "Autonomous Robotic Stone Stacking with Online next Best Object Target Pose Planning". In: IEEE, May 2017, pp. 2350–2356. DOI: 10.1109/ICRA.2017.7989272.

[132] Richard K. Untermann. *Principles and Practices of Grading, Drainage, and Road Alignment: An Ecologic Approach*. Reston, Va: Reston Pub. Co, 1978.

[133] Allen Richard Reece. "The Fundamental Equation of Earth-Moving Mechanics". In: *Proceedings of the Institution of Mechanical Engineers, Conference Proceedings* 179.6 (June 1964), pp. 16–22. DOI: 10.1243/PIME_CONF_1964_179_134_02.

[134] *UgCS for Ground Penetrating Radar (GPR) Surveys*. URL: https://www.ugcs.com/page/ugcs-for-ground-penetrating-radar-surveys (visited on 03/27/2020).

[135] George Stiny and James Gips. "Shape Grammars and the Generative Specification of Painting and Sculpture". In: *Segmentation of Buildings for 3DGeneralisation. In: Proceedings of the Workshop on Generalisation and Multiple Representation*. Leicester, 1971.

[136] George Stiny and William J. Mitchell. "The Grammar of Paradise: On the Generation of Mughul Gardens". In: *Environment and Planning B: Planning and Design* 7.2 (1980), pp. 209–226. DOI: 10.1068/b070209.

[137] Terry Knight and George Stiny. "Making Grammars: From Computing with Shapes to Computing with Things". In: *Design Studies* 41 (Nov. 2015), pp. 8–28. DOI: 10.1016/j.destud.2015.08.006.

[138] Nick Callicott. *Computer-Aided Manufacture in Architecture: The Pursuit of Novelty*. Oxford: Architectural Press, 2001.

[139] Tobias Bonwetsch, Fabio Gramazio, and Mathias Kohler. "Digitales Handwerk". In: *GAM 06. Nonstandard Structures*. Vol. 6. Vienna: Springer, 2013. URL: http://public.ebookcentral.proquest.com/choice/publicfullrecord.aspx?p=4217826 (visited on 06/02/2020).

[140] *Robotic Fabrication for COMPAS*. URL: https://gramaziokohler.github.io/compas_fab/ (visited on 05/05/2020).

[141] *Dynamic*. In: *Merriam-Webster.Com*. URL: https://www.merriam-webster.com/dictionary/dynamic (visited on 08/06/2020).

[142] Rivka Oxman. "Theory and Design in the First Digital Age". In: *Design Studies* 27.3 (May 2006), pp. 229–265. doi: 10.1016/j.destud.2005.11.002.

[143] Margitta Buchert, ed. *Reflexive design*. Berlin: Jovis, 2014.

[144] Nigel Cross. *Design Thinking: Understanding How Designers Think and Work*. Engl. ed. Oxford: Berg, 2011.

[145] David Wang and Linda N. Groat. *Architectural Research Methods*. Second Edition. Hoboken: Wiley, 2013.

[146] W.L. Myers, N. Kong, and G.P. Patil. "Topological Approaches to Terrain in Ecological Landscape Mapping". In: *Community Ecology* 6.2 (Dec. 2005), pp. 191–201. doi: 10.1556/ComEc.6.2005.2.7.

[147] Gunther Weber, Peer-Timo Bremer, and Valerio Pascucci. "Topological Landscapes: A Terrain Metaphor for Scientific Data". In: *IEEE Transactions on Visualization and Computer Graphics* 13.6 (Nov. 2007), pp. 1416–1423. doi: 10.1109/TVCG.2007.70601.

[148] Igor V. Florinsky. *Digital Terrain Analysis in Soil Science and Geology*. 1st ed. Amsterdam ; Boston: Elsevier/Academic Press, 2012.

[149] Ludovic Duponchel. "When Remote Sensing Meets Topological Data Analysis". In: *Journal of Spectral Imaging* (Feb. 6, 2018). doi: 10.1255/jsi.2018.a1.

[150] Michael Beaman. "Landscapes After The Bifurcation of Nature: Models for Speculative Landformations". In: *Posthuman Frontiers: Data, Designers, and Cognitive Machines: Projects Catalog of the 36th Annual Conference of the Association for Computer Aided Design in Architecture*. ACADIA. Ann Arbor, 2016, pp. 432–439.

[151] Karola Dierichs and Achim Menges. "Aggregate Structures: Material and Machine Computation of Designed Granular Substances". In: *Architectural Design* 82.2 (Mar. 2012), pp. 74–81. doi: 10.1002/ad.1382.

[152] Mathias Rippmann. "Funicular Shell Design: Geometric Approaches to Form Finding and Fabrication of Discrete Funicular Structures". PhD Thesis. ETH Zurich, Department of Architecture, 2016.

[153] Ignasi de Solá-Morales and Cynthia Davidson. "Terrain Vague". In: *Anyplace*. Cambridge, MA: MIT Press, 1995, pp. 118–123.

[154] *Zentrumsgemeinde Im Oberen Gürbetal*. url: https://www.wattenwil.ch/guerbe (visited on 10/09/2019).

[155] Robert Smithson. "The Monuments of Passaic". In: *Artforum* 7.1 (1967), pp. 52–57.

[156] *Point Cloud Library (PCL)*. url: https://pointclouds.org/ (visited on 07/02/2020).

[157] *Python ROS Bridge Library (Roslibpy)*. url: https://roslibpy.readthedocs.io/en/latest/ (visited on 04/02/2020).

[158] *Robotic Operating System (ROS)*. URL: https://www.ros.org/ (visited on 07/02/2020).

[159] Bradley Cantrell and Zihao Zhang. “A Third Intelligence”. In: *Landscape Architecture Frontiers* 6.2 (2018), p. 42. DOI: 10.15302/J-LAF-20180205.

[160] Mario Carpo. *The Alphabet and the Algorithm*. Writing Architecture. Cambridge, Mass: MIT Press, 2011.

Relevant Publications by the Author

Main Author

Ilmar Hurkxkens, Benedikt Kowalewski, and Christophe Girot. “Informing Topology: Performative Landscapes with Rapid Mass Movement Simulation”. In: *JoDLA. Journal of Digital Landscape Architecture*. Ed. by Erich Buhmann, Stephen Ervin, Sigrid Hehl-Lange, and James Palmer. Berlin: Wichmann Verlag, 5-2020, pp. 130–137. doi: 10.14627/537690014.

Ilmar Hurkxkens, Ammar Mirjan, Fabio Gramazio, Matthias Kohler, and Christophe Girot. “Robotic Landscapes: Designing Formation Processes for Large Scale Autonomous Earth Moving”. In: *Impact: Design With All Senses. Proceedings of the Design Modelling Symposium, Berlin, 2019*. Ed. by Christoph Gengnagel, Olivier Baveral, Jane Bury, Mette Ramsgaard Thomsen, and Stefan Weinzierl. Cham: Springer International Publishing, 2019, pp. 69–81. doi: 10.1007/978-3-030-29829-6_6.

Ilmar Hurkxkens and Mathias Bernhard. “Computational Terrain Modeling with Distance Functions for Large Scale Landscape Design”. In: *JoDLA. Journal of Digital Landscape Architecture*. Ed. by Erich Buhmann, Stephen Ervin, Sigrid Hehl-Lange, and James Palmer. Berlin: Wichmann Verlag, 4-2019, pp 222–230. doi: 10.14627/537663024.

Ilmar Hurkxkens, Christophe Girot, and Marco Hutter. “Robotic Landscapes: Developing Computational Design Tools Towards Autonomous Terrain Modeling”. In: *Disciplines & Disruption. Proceedings of the 37th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*. Ed. by Takehiko Nagakura, Skylar Tibbits, Mariana Ibañez, Caitlin Mueller. Cambridge, MA: 2017, pp. 292–297.

Ilmar Hurkxkens. “Instruments of Design: On Surveying and Designing Site-Specific Material”. In: *Field Instruments of Design*. Ed. by Christophe Girot and

Ilmar Hurkxkens. Pamphlet 19. Zurich: gta Verlag, 2015, pp 23–33.

Ilmar Hurkxkens and Georg Munkel. "Speculative Precision: Combining Haptic Terrain Modelling with Real-Time Digital Analysis for Landscape Design." In: *Peer Reviewed Proceedings of Digital Landscape Architecture Conference at the ETH Zurich (DLA)*. Berlin: Wichmann Verlag, 2014, pp 399–405.

Co-Author

Christophe Girot and Ilmar Hurkxkens. "Robotic Landscapes: Nature, Computation, and the Design Space of Autonomous Terrain Modeling". In: *Landscape Architecture Frontiers* 6.2 (2018), p. 64–75. DOI: 10.15302/J-LAF-20180208.

Melsom, James, Luis Fraguada, and Ilmar Hurkxkens. 2017. "Onsite Analysis: Developing a Flexible Software Field-Kit for Landscape Architecture and Spatial Design". In: *JoDLA Journal of Digital Landscape Architecture*. Ed. by Erich Buhmann, Stephen Ervin, Sigrid Hehl-Lange, and James Palmer. Berlin: Wichmann Verlag, 2-2017, pp 262–270. DOI: 10.14627/537629027.

James Melsom, Christophe Girot, and Ilmar Hurkxkens. "Directed Deposition: Exploring the Roles of Simulation and Design in Erosion and Landslide Processes". In: *Computational Ecologies: Design in the Anthropocene. Proceedings of the 35th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*. Ed. by Lonn Combs and Chris Perry. Cincinnati, Ohio: 2015, pp 211–221.

This dissertation is designed and typeset by the author in KP-Fonts using LaTeX and printed by OK DigitalDruck AG in Zurich on Rebello matt, 100% FSC recycled paper. All images by the author unless stated otherwise. Topographic data from *swisstopo*. © Ilmar Hurkxkens, 2020.

ETH Zurich 2020