Rammed Earth

Exploring the material's potential to address residential challenges within Central European suburbs.

research paper

aE Studio

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Figure 1 [cover page]
A landfill site for the deposition of non-hazardous soil excavations in Weiach, Switzerland.

Keywords

rammed earth, circular processes, prefabrication,
local resources, simplicity, climate control, flexibility

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Abstract

The currently mostly inefficient resource management neglects valuable existing stocks, and grey energy and emissions contribute to a building sector misaligned with climate goals. Amid these challenges, rammed earth, an ancient material, is experiencing a sustainable construction resurgence by transforming under-utilized non-hazardous soil excavations into a building material. However, traditional on-site fabrication is expensive and labour-intensive. While recent attention has sparked innovations in prefabrication, the rammed earth field remains a niche lacking strategies for large-scale use. The investigation of four already existing methods of prefabrication combined with requirements in sub-urban residential housing generates a strategy of how the use of the material can be scaled up considering aspects of efficiency, circularity, and aesthetics.

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introduction

In the contemporary global context, the scarcity of resources is unmistakable: In 2023, the utilization exceeded the amount on the planet that can be recovered annually by a factor of 1.7. This dates the so-called Earth Overshoot Day, by which all available resources of that year are consumed, to August 2, leaving an ecological deficit for the remaining nearly five months of the year (Global Footprint Network 2023). Concurrently, the approach to resources lacks efficiency, as opposed to a concerted effort to judiciously utilize them, numerous valuable, already existing stocks are neglected. Moreover, grey energy, meaning primary energy which is necessary to facilitate the life-cycle of a product from raw material mining to disposal, as well as grey emissions, meaning the resulting share of non-renewable energy consumption or chemical reactions in manufacturing processes (Gebäudeforum Klimaneutral 2022), contribute to a building sector which is not in line with the current set, and for climate protection indispensable, goals (United Nations Environment Program 2022, xvii).

Amidst these challenges, the ancient material rammed earth is witnessing a renaissance in the realm of sustainable construction materials. Worldwide renowned examples like the Chinese Wall often surprise by the fact that still existing, sometimes 2200-year-old parts consist of rammed earth (Schroeder 2019, 4). Equally, European structures, like the 6-storey high and still-in-use residential building Haus Rath in Weilburg, Germany from 1830, seen in Figure 2, testify to the far-reaching history of the material (Schroeder 2019, 16), which, however, largely disappeared from the public eye and is just now being rediscovered. Challenging the current issue of inefficiently deployed resources, rammed earth has the potential

Figure 2

The highest rammed earth building in Germany, called "Haus Rath", was built in 1830.

to make use of the abundant under-utilized, and mostly as waste denoted, non-hazardous soil excavations, which are widely available in almost all parts of the world (Statistisches Bundesamt 2022, 34). Furthermore, consisting of a purely mineral mix of compressed earth-moist loam, meaning sand, silt and clay, and gravel, it has optimum prerequisites for circular use, in which rammed earth elements can be crushed and re-moistened into the raw material in theoretically endless cycles (Schroeder 2019, 172).

Examining the context of Central Europe, in particular sub-urban regions, the characteristic erection of multi-family residential buildings with four stories or less (Bundesamt für Statistik, 2023), exemplarily illustrated for Switzerland in Figure 3, offers potential for the substitution of non-sustainable building materials with rammed earth, which inherits the load-bearing capacities for those dimensions. Especially massive structures out of concrete and masonry, which contain large amounts of grey energy and emissions, come into consideration due to the similarity in construction typology. Thus, the design objective is to create a circularly applicable housing construction system for these areas, which uses secondary soil excavations for prefabricated rammed earth elements. Furthermore, the system shall make use of the great prerequisites for passive climate control of rammed earth, achieved by its high thermal mass and its vapor openness (Sauer and Kapfinger 2015, 65), which could replace current mostly active climate strategies in residential buildings (European Environment Agency 2022, 5). On a societal level, the design focus is to bridge one general challenge found in most suburbs, namely social segregation, which is often expressed in the spatial distinctions of areas with predominantly single-family houses, and such with high-rises (Klausen, Erling, and Røe 2012, 1), by representing an intermediate density and offering diverse floorplan concepts and social functions. Of special interest are also the uncommon aesthetics of rammed earth in sub-urban areas, where the material can hold the potential to create new forms of identification with the neighbourhood for its residents.

The research paper focuses on the key challenge within the establishment of the described rammed earth system, which can be identified in its traditional fabrication on-site. This method requires a high amount of manual labour, thus making the construction very expensive (Sauer and Kapfinger 2015, 10), resulting in long construction schedules, and requiring specialized planners and workers (Sauer and Kapfinger 2015, 118). The material has already attracted more attention in recent years, leading to new developments to bridge tradition and innovation, especially by methods of prefabrication. However, the field of rammed earth is still a niche, thus lacking the infrastructure necessary to make waste streams of non-hazardous soil excavations fully usable on a larger and more efficient scale, and to prefabricate locally in multiple regions of Central Europe. The research paper aims to create an

understanding of the current values and bottlenecks of already existing methods of prefabrication, in order to develop a strategy that can be used as a prerequisite for the design of the rammed earth housing system.

The guiding research question is: How can advancements in rammed earth prefabrication allow for broader use of the material in multi-family residential buildings in the sub-urban Central European context?

This question is divided into the two sub-questions:

Q1.What are the current values and bottlenecks in the prefabrication of rammed earth elements that influence their efficiency, circularity, and aesthetics?

Q2. How can prefabricated rammed earth elements be used in a modular way that responds to requirements for housing purposes?

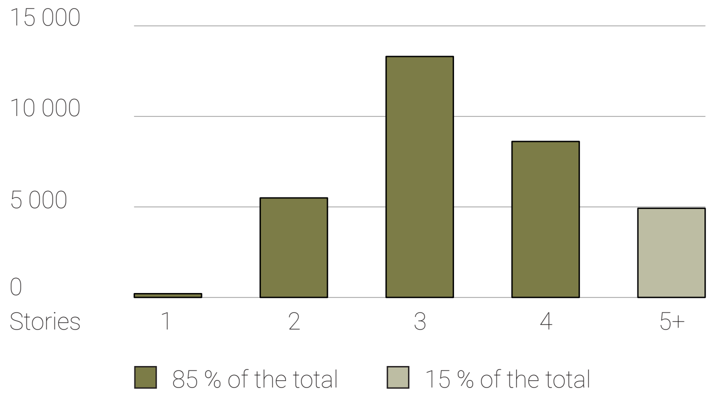


Figure 3
The diagram shows the number of newly erected multi-family residential houses in Switzerland 2022, structured in their number of stories.

methodology

To address the posed research questions, it was chosen to use the tool of case study analysis by value chain mapping and the comparison via a Pugh Matrix, as well as literature review.

To approach Q1, four already existing methods of prefabrication are chosen, which all show different strategies in the handling of the material rammed earth. Those case studies are selected based on the premise of the sole use of unstabilized rammed earth in their production, and the actual implementation of the produced elements in real building projects. The description and assessment are based on the prefabrication of one solid wall element without supplemental specifications such as lintels, or erosion breaks. The case studies are researched through site visits and textual, photographic and videographic material. From that, value chain diagrams are created, which identify added value and existing bottlenecks throughout the respective processes. A template is used to delineate all information found within the three categories efficiency, circularity, and aesthetics, in parallel to the different life-cycle stages of rammed earth (see Figure 4). To allow for an overview of the identified parameters and to facilitate an assessment of the different case studies, the tool of a Pugh matrix is used to transform the qualitative data into comparable parameters. For this, different criteria along the life-cycle of rammed earth are classified, within which a scoring system differentiates between the best case +1, a neutral option 0, and one to be assessed negatively -1, guided by the previously identified added values and bottlenecks. Parameters, which are regarded as particularly meaningful, are weighted stronger and thus have more influence on the final result.

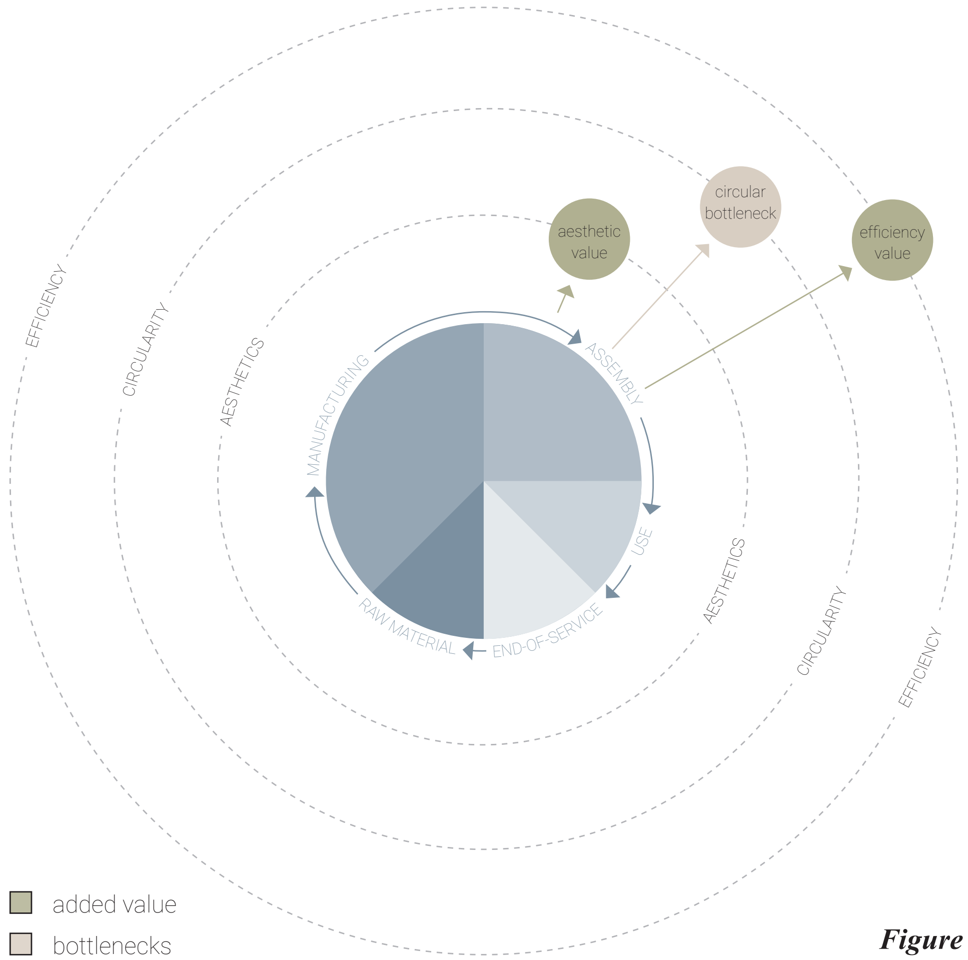


Figure 4

To investigate Q2, a literature review is conducted to work out the requirements of housing blocks to create an understanding of the standards rammed earth elements have to meet to allow for residential purposes. Lastly, the different parameters of the Pugh matrix are assessed according to their potential to facilitate rammed earth production on a larger scale within Central Europe. Subsequently, via the selection and combination of different aspects, a prototype of a new value chain is developed, to draw as close to the optimum set parameters as possible. This value chain serves as a prerequisite and basis for the design of the housing system and its constituent elements.

3

results

Case Studies

off-site prefabrication

Warburg, Germany

August Lücking GmbH & Co. KG

The brick factory August Lücking was founded in 1899 and is currently run by the fifth family generation. The industrial company is specialized in the production of bricks, pre-cast concrete elements, and prefabricated brick elements (Lücking 2020). At the end of 2023, they started producing and selling prefabricated rammed earth elements in collaboration with the clay specialists Conluto (DE) and ClayTec (DE), intending to broaden the product palette towards more sustainable building solutions, whilst making use of the already existing factory infrastructure. Consulting, offer and order are taken over by Conluto and ClayTec, whilst production and delivery are performed by August Lücking. Distinctive in the business system is the offer of individual rammed earth walls as a product with precise planning of costs, construction times and processes, and with a predicted production two to three weeks after the order is placed, and another two to three weeks of drying time before delivery (ClayTec 2023, 7).

PROCESS (see Figure 13):

On the production site in Warburg, August Lücking has its own clay pit, from which the rammed earth ingredient is extracted. The clay is then transported to the factory sites of Conluto and ClayTec at a distance of around 50 kilometres, respective 100 kilometres. There, the final rammed earth blend with the remaining parts of sand, silt and gravel is mixed, and eventually transported back to August Lücking. The availability of five different colours of rammed earth mixture adds a customizable aesthetic dimension to the prefabricated elements. A production hall on the company's premises, used for their full range of prefabricated elements, is also the location where the rammed earth material gets

stored and further processed (see Figures 5 and 6). Initially acquired for the manufacturing of brick walls, a semi-automatic masonry unit can be transformed into a line to compact rammed earth layers (see Figure 7). For that, the distribution container that usually slides along the track to apply mortar in between each layer of brick is replaced with a vibrating plate. Each rammed earth wall is manufactured to predefined measurements. According to those, a concrete foundation is placed at the bottom as the base of the wall for later transport, as well as protection from ascending water in the use phase (see Figure 8). Formwork is applied as needed for the desired measurements, and subsequently, the raw material is inserted and pre-compacted by the vibrating plate in layers (see Figure 9). Each layer furthermore requires manual re-compaction with hand-operated pneumatic tampers (see Figure 10). Once the desired height is reached, the formwork is removed, and the semi-automatic masonry unit can slide along tracks on the floor to the position of the following wall. In winter, exhaust heat from the brick oven is used to warm up the hall, facilitating a quicker drying process.

The operation of the process requires two workers and results in elements weighing a maximum of 10 tons, with a compressive strength of approximately 5.0 N/mm². These elements exhibit thicknesses ranging from 15 to 50 cm, lengths reaching a maximum of 700 cm, and heights of up to 300 cm. The adjustment of element measurements to the required wall specifications eliminates the need for touch-ups of joints during assembly. Transportation of the prefabricated rammed earth elements to the construction site is facilitated by an inloader with a maximum weight capacity of 20 tons (see Figures 11 and 12). The cost of rammed earth walls is estimated by August Lücking at 400-500€ per m².

Figure 5

The production hall used for all prefabricated elements of August Lücking.

Figure 6

The raw material is stored in the back of the hall and covered with a plastic sheet to protect it from drying out.

Figure 7

The semi-automated masonry unit, originally installed to prefabricate brick walls, can be used to compact layers of rammed earth by exchanging the container for brick mortar to a vibrating plate.

Figure 8

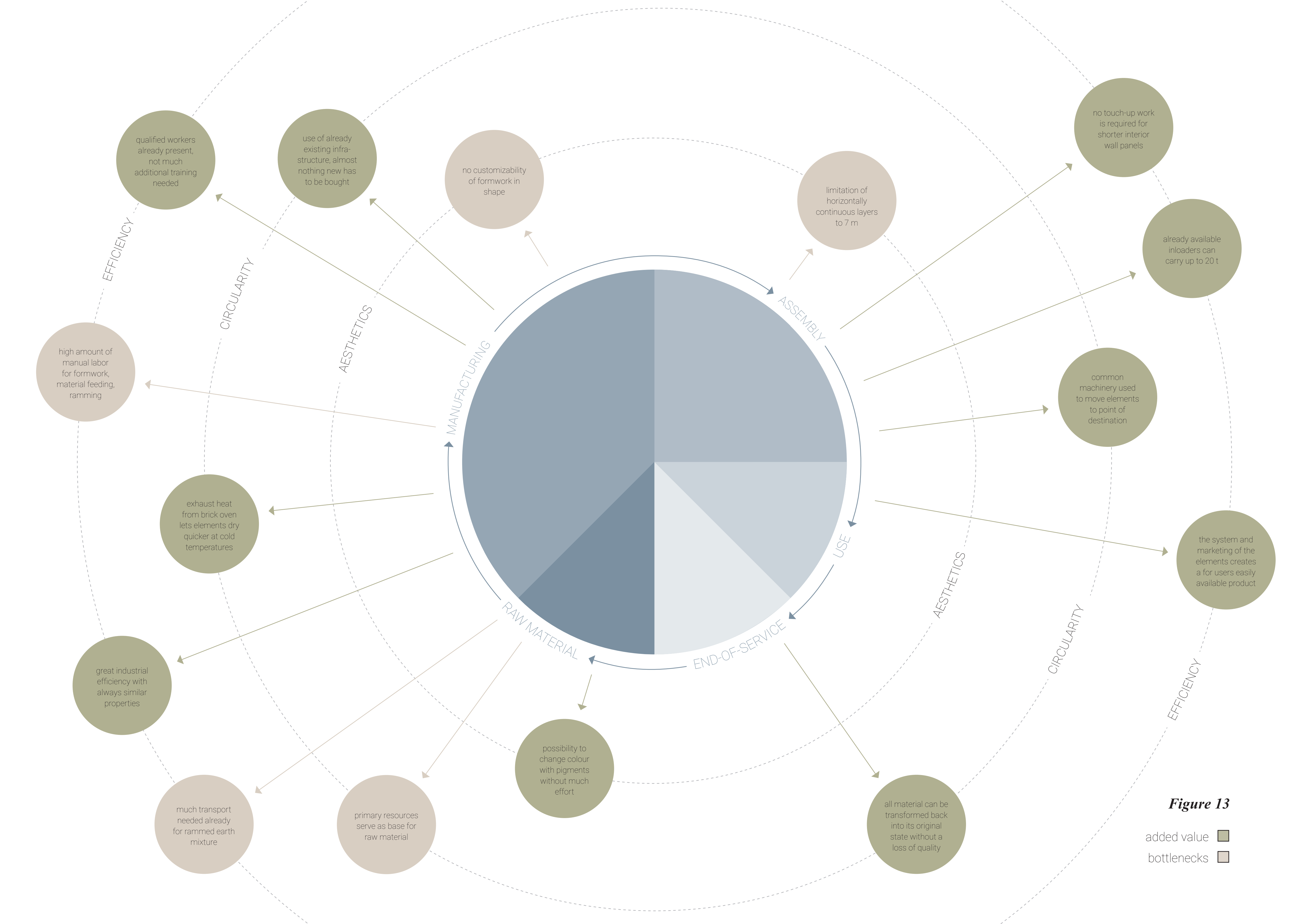
A finished prefabricated rammed earth element with a concrete base for transport and to protect against ascending water.

Figure 9
Formwork is applied for the elements as needed.

Figure 10
Two manual pneumatic tampers are used to further compress each rammed earth layer.

Figure 11
Prefabricated elements are transported with inloaders.The inloader palette is lifted with a crane on tracks.

Figure 12
Multiple walls can be stored on an inloader. If stored outside, they need to be covered to stay protected from the rain.



MANUFACTURING
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RAW MATERIAL
EFFICIENCY
CIRCULARITY
AESTHETICS
AESTHETICS
CIRCULARITY
EFFICIENCY
qualified workers already present, not much additional training needed
use of already existing infra-structure, almost nothing new has to be bought
no customizability of formwork in shape
limitation of horizontally continuous layers to 7 m
no touch-up work is required for shorter interior wall panels
already available inloaders can carry up to 20 t
common machinery used to move elements to point of destination
the system and marketing of the elements creates a for users easily available product
high amount of manual labor for formwork, material feeding, ramming
exhaust heat from brick oven lets elements dry quicker at cold temperatures
great industrial efficiency with always similar properties
much transport needed already for rammed earth mixture
primary resources serve as base for raw material
possibility to change colour with pigments without much effort
all material can be transformed back into its original state without a loss of quality
added value
bottlenecks

Figure 13

off-site prefabrication

Schlins, Austria

Lehm Ton Erde Baukunst GmbH

The pioneering company Lehm Ton Erde was founded in 1984 by the figurehead Martin Rauch and has since then made substantial contributions to the revival and progress of rammed earth, with more than one hundred realized projects and multiple publications. Specifically, the invention of its prefabrication line for rammed earth elements, called "Roberta", is leading the way towards establishing the material in the mainstream building sector (Erden, n.d.).

PROCESS (see Figure 22):

The raw material utilizes soil excavations and landfill material from the surrounding area. The materials undergo a dual sorting process, in which they are pre-filtered at the landfill sites or by the excavation companies and subsequently at the Lehm Ton Erde fabrication hall. There, also the final rammed earth mix is created. The prefabrication process is semi-automatically executed by the specially developed "Roberta" and requires the assistance of 2-3 workers (see Figure 14). The basic operational system involves moving along a 40-meter-long formwork, producing one layer of rammed earth at a time (see Figure 15). Afterwards, the machine slides back to the starting point and repeats the process. The sequence of operations begins with filling a large container at the back of themachine with the raw material and installing the formwork to the desired wall thickness, which can range between 7 and 85 centimetres. A conveyor belt then transports the material towards an output located above the formwork (see Figure 16). A levelling board behind the output ensures uniformity in material height, followed by the pre-compaction of

the material using vibrating plates (see Figure 17). Afterwards, smaller pneumatic tampers further compact the edges of the formwork (see Figure 18). Additionally, the fabrication involves testing through the creation of test cubes every few layers, ensuring ongoing quality.

Upon completion of the layering process, which takes approximately 3 to 4 days, the formwork is removed. The 40-meter-long prefabricated wall is then segmented into individual elements of required lengths using a saw blade (see Figure 19). To facilitate this process, palettes are strategically placed below the first layer of rammed earth, aligning with the final element sizes and allowing the saw blade to cut through the gaps between the palettes. The individual elements can then be transported by a crane on tracks within the fabrication hall, where most of the space is allocated to storing and drying prefabricated walls. Transport to the construction site is done via truck, and elements are lifted by crane to its destined position (see Figure 20). During production, wooden slats were inserted crosswise below the bottom rammed earth layer, and removed upon completion of the wall, to allow for carry straps to be inserted in the notches. The resulting gaps in the wall are manually touched up (see Figure 21).

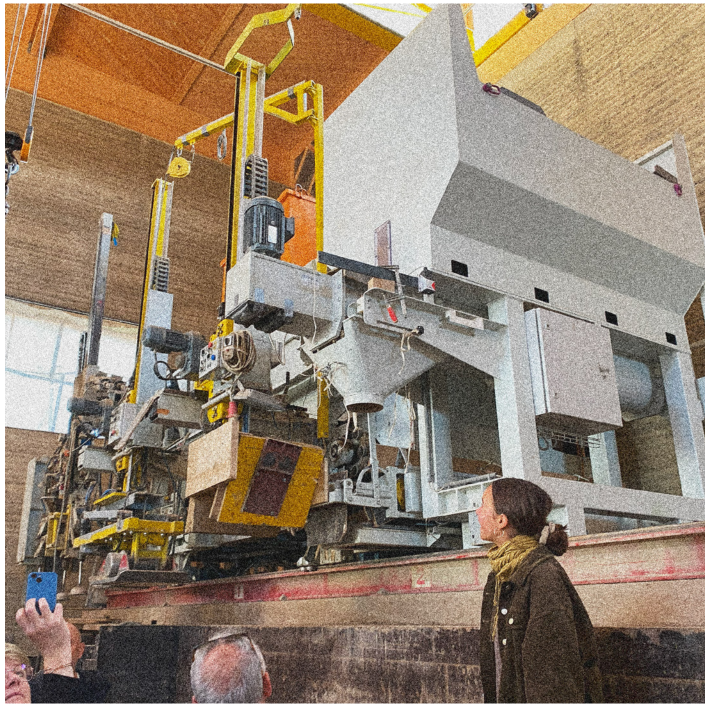


Figure 14
The so-called "Roberta".

Figure 15
The 40m long line for prefabrication with the already placed pallets and the disassabled formwork.

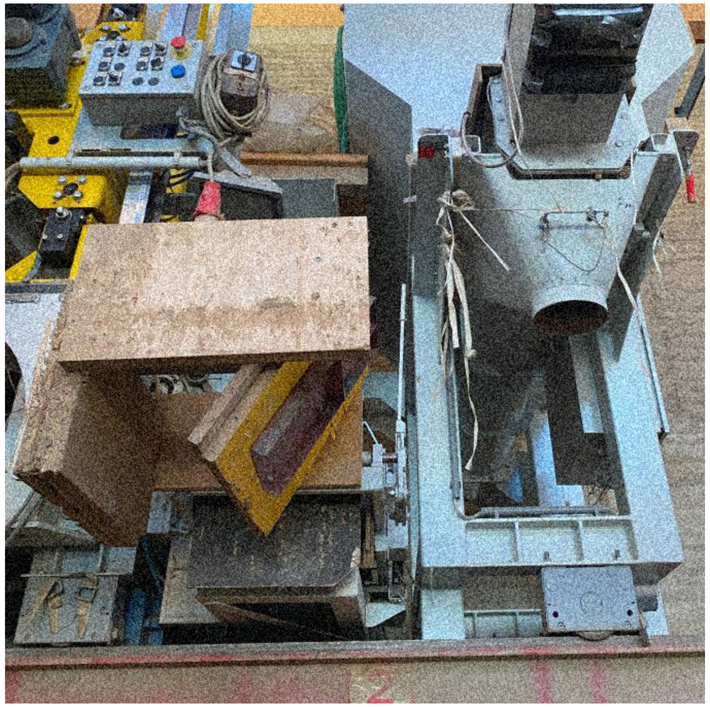


Figure 16
The outlet for rammed earth material, which is centred above the formwork.

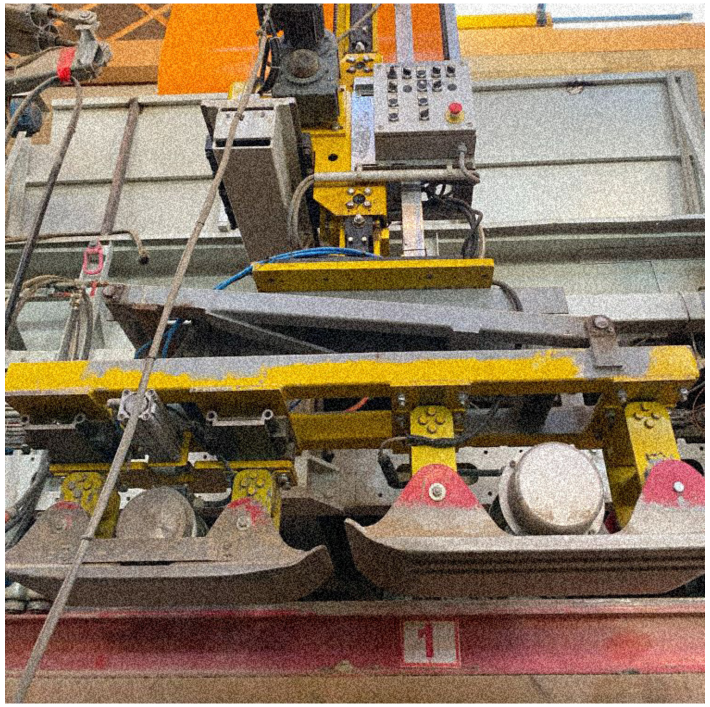


Figure 17
The pre-compaction is done by these two large steel feet.

Figure 18

The more precise compaction is being done by these rammers, that can also go into corners and along edges.

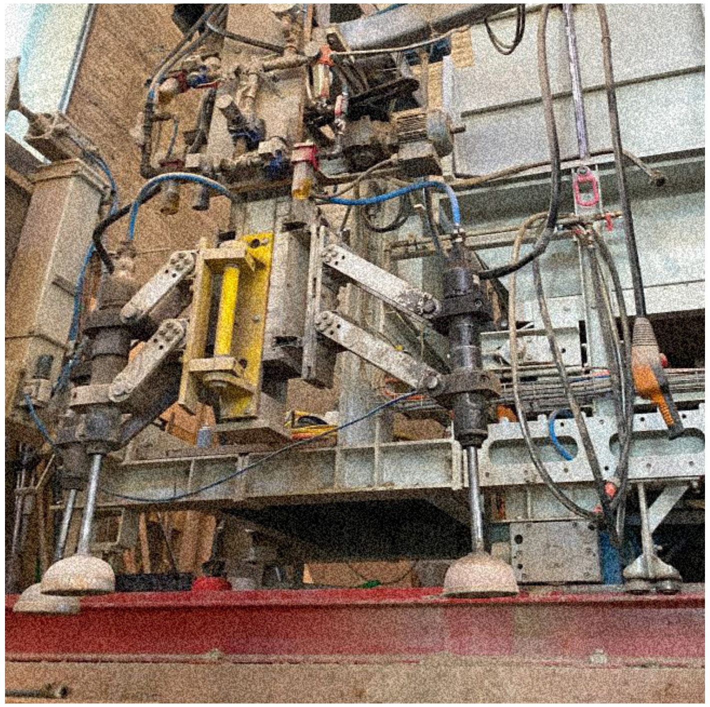


Figure 20

The finished elements are transported via truck and lifted to the final position on the construction site.

Figure 19

In the end, the 40m long prefabricated wall gets cut up into the required lengths.

Figure 21

Once assembled using clay mortar, the joints in between elements have to be manually touched-up to be less visible and prone to erosion.

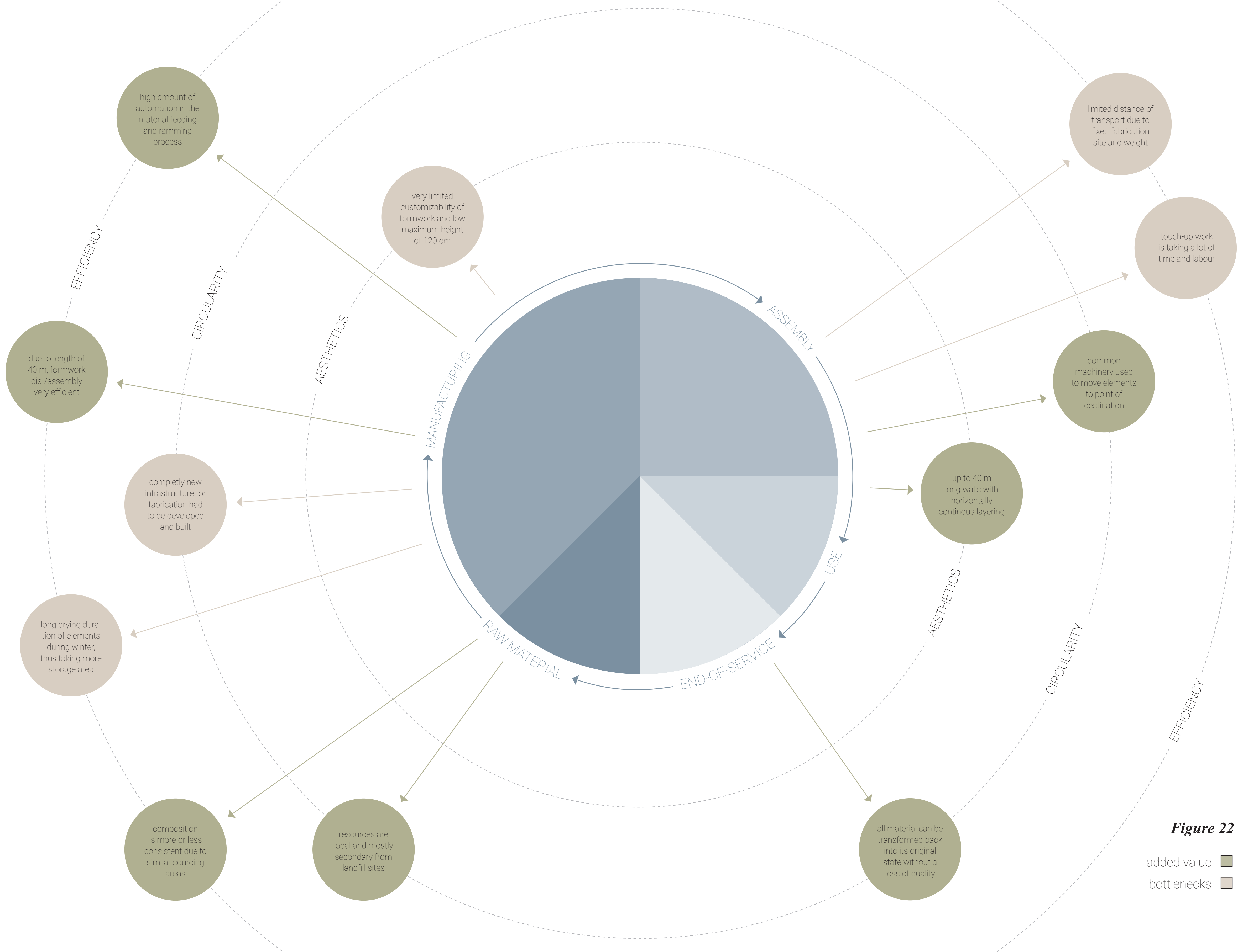


Figure 22

added value
bottlenecks

off-site prefabrication

Laufenburg, Switzerland

ERNE AG Holzbau

The industrial company is part of the larger Erne Group and develops and produces buildings and products based on timber with means of modern technology and prefabrication (Erne, n.d.). For the extension of their office, which was built in 2023, Erne Holzbau decided to complement the hybrid timber main structure with two eleven-meter-high cores out of self-supporting rammed earth for the staircase and sanitary facilities, using their robotic fabrication capabilities, centered around a commercial pneumatic rammer (Modulart 2023). Since completing this first project, Erne has been looking for further projects that allow the implementation of rammed earth (Bucher 2023, 14:30), possibly with prefabrication of elements on the Erne premises and subsequent delivery to the respective construction site (Bucher 2023, 16:25), or by installing the production line close-by to the building site (Modulart 2023).

PROCESS (see Figure 31):

In the case of their office extension, Erne Holzbau was fortunate that the excavations of the building site were suitable for use as rammed earth, with only gravel needing to be added (Gomaa, Schade, Bao, and Xie 2023, 11). The material was mixed whilst still in the excavation pit (see Figure 23) and stored close by, accompanied by extensive testing (Modulart 2023). For the production itself, the needed infrastructure was set up in an existing logistic tent of the company (Bucher 2023, 7:50). The fabrication system followed a specific sequencing, involving three parallel production zones, between which the robot was able to vary by running on a rail

(Bucher 2023, 8:30). This way, the general cycle of formwork assembly, material deposition, robotic ramming, formwork disassembly, and transport to the storage area, was possible to happen simultaneously for three wall elements without any idle time of the robot (Gomaa, Schade, Bao, and Xie 2023, 11) (see Figure 24).

For further optimization, an industrial hopper was developed, which allowed for easier portioning when filling in rammed earth layers with an excavator (Modulart 2023) (see Figures 25 and 26), the reinforced and adjustable timber formwork was equipped with a special mechanism for quick assembly and disassembly (Gomaa, Schade, Bao, and Xie 2023, 11) (see Figure 27), and all elements were priorly planned in 3D, allowing the robot to later refer to those digital plans in production (Bucher 2023, 7:30) (see Figures 28 and 29).

With this system 6 to 9 elements were created on the average 12-hour working day of Erne Holzbau (Bucher 2023, 9:20). The finished elements were equipped with individual QR codes to track their final destination (Modulart 2023), and stored in a parking garage, where they dried for 6 to 8 weeks. Afterwards, they were stacked on top of each other using a clay mortar, and the joints were touched-up using the initial rammed earth material (Bucher 2023, 9:00). Due to the design requirements, but also the limits of lifting tools and the entrance gate to the parking garage, the elements had maximum dimensions of 300 centimetres in length, 125 centimetres in height, 35 centimetres in width, and 3 tons in weight (Bucher 2023, 10:30) (see Figure 30).

Figure 23
The rammed earth soil was already pre-mixed in the excavation pit.

Figure 24
The rail behind the three production boxes allows for the robot to alternate after each rammed layer to another element, to allow for new material to be refilled.

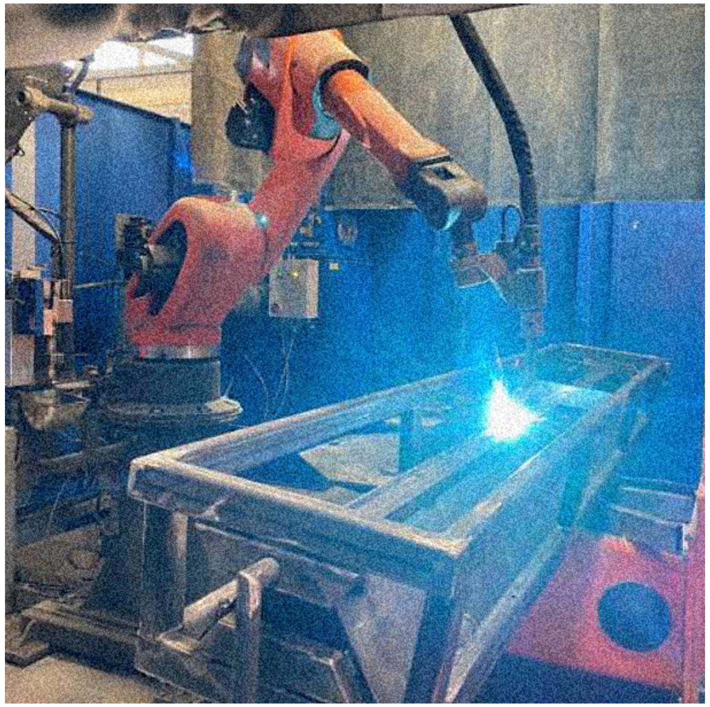


Figure 25
An industrial hopper was developed to allow for material to be easier portioned.

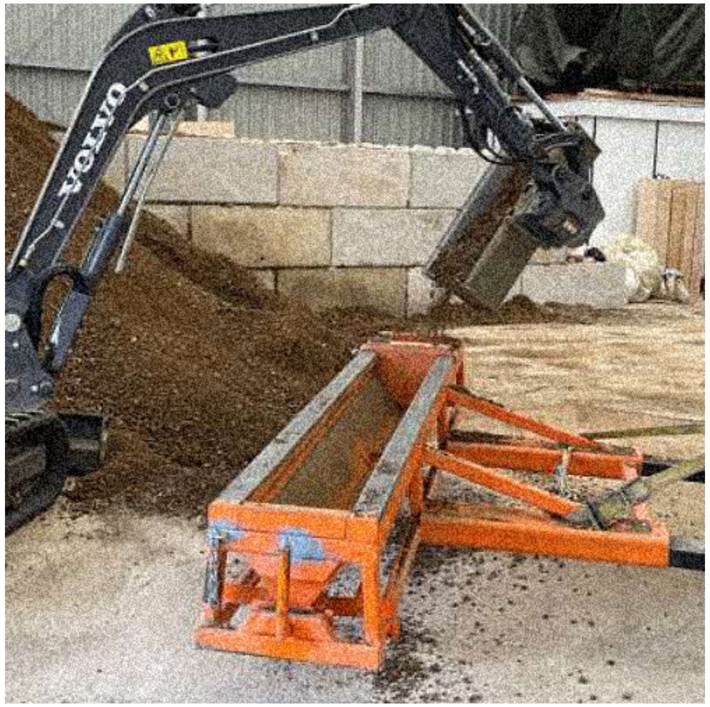


Figure 26
The industrial hopper is then filled with the rammed earth material.

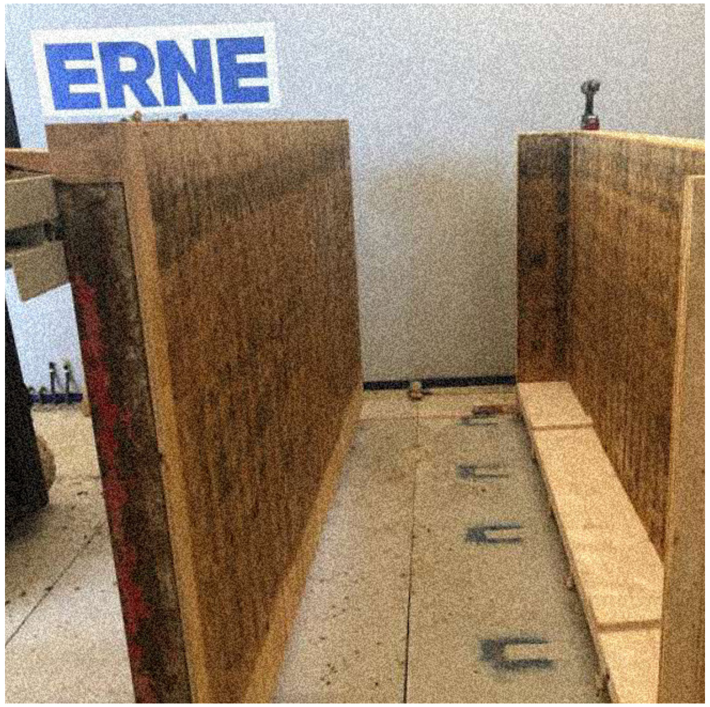
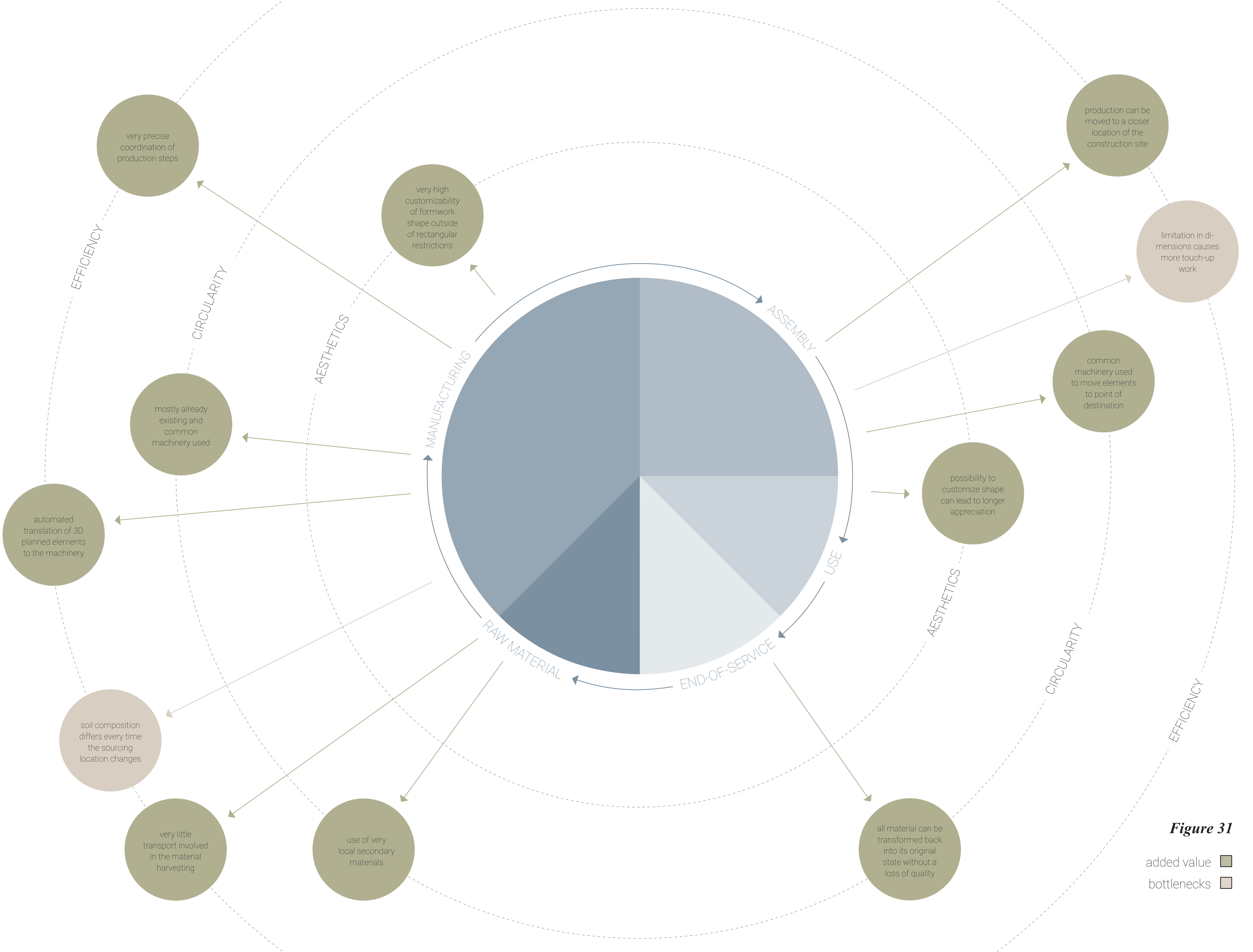


Figure 27
Formwork was conceptualized to be easily assembled and disassembled.

Figure 28
The robot reaches over and inside the form-work to compact the layers.

Figure 29
The robotic arm is equipped with a pneu-matic rammer.

Figure 30
The final elements were stacked upon each other in a brick-like manner.



EFFICIENCY
CIRCULARITY
AESTHETICS
MANUFACTURING
ASSEMBLY
USE
END-OF-SERVICE
RAW MATERIAL
very precise coordination of production steps
very high customizability of formwork shape outside of rectangular restrictions
production can be moved to a closer location of the construction site
limitation in di-mensions causes more touch-up work
common machinery used to move elements to point of destination
possibility to customize shape can lead to longer appreciation
mostly already existing and common machinery used
automated translation of 3D planned elements to the machinery
soil composition differs every time the sourcing location changes
very little transport involved in the material harvesting
use of very local secondary materials
all material can be transformed back into its original state without a loss of quality
AESTHETICS
CIRCULARITY
EFFICIENCY
added value
bottlenecks

Figure 31

on-site prefabrication

Chambles, France

Le Pisé

Nicolas Meunier, head of the earth-building company Le Pisé, first started experimenting with rammed earth prefabrication in 1986. Later, the company developed a portable prefabrication station, which can be transported via truck to prefabricate directly on-site or nearby, given the respective conditions of the project's location (Le Pisé, n.d.).

Process (see Figure 40):

The approach to prefabrication is characterized by a strong prioritization of hyper-local aspects. The raw material is sourced, depending on the project, as close to the construction site as possible, for which samples of the materials are tested and assessed for their suitability (Jeske 2020, p. 5). The mobile prefabrication station then arrives at, or close to the construction site via truck, determined by the availability of space (see Figure 32).

To operate the station, two people are needed. Soil is filled in large quantities of 6m³ onto a motorized conveyor belt (Trouillet 2021, 67), and then transferred to a mixer (see Figure 33). There, a sieve on top sorts out larger stones, to create the correct composition for the following adjustment of moisture content in the mixer (see Figure 34). Subsequently, the processed material is manually loaded into a drawer, which is slid on a rail towards the formwork (see Figure 35). Once positioned above it, the bottom of the drawer is opened, and the material is released into the formwork (Le Pisé 2019, 1:32).

The levelling of each rammed earth layer and a slight pre-compaction using a wooden rammer is done manually (Le Pisé 2019, 2:12) (see Figure 36). The full compaction is executed by four dropping weights of twenty kilograms each, lifted by compressed air and guided by a worker (Jeske 2020, p. 6) (see Figures 37 and 38). This process is repeated for each layer until the desired height is reached.

Upon completion of one element, the formwork is removed manually. Depending on the complexity of the element shape, between two and five blocks can be produced per day. These are then stored nearby, depending on the availability of the storage area, to allow for drying (Trouillet 2021, 67). To facilitate transportation, threaded rods are rammed into the bottom layer of the elements, serving as temporary handles (see Figure 39). These rods are removed upon installation, and the resultant holes are manually filled with clay and retouched (Pilz 2022, 33). For the assembly of individual blocks, earth mortar is made from the same material, and sieved to remove the largest grains (Trouillet 2021, 32). Lightweight mobile construction cranes are used to move the blocks to their final destination (Jeske 2020, p. 6).

Figure 32
The fabrication station can be transported with a conventional truck.

Figure 33
The raw material is stored on top of the station and is transferred towards a mixer with a sieve on top.

Figure 34
The sieve sorts out larger stones that are unsuitable for the mixture.

Figure 35
The final rammed earth material is portioned manually by loading a drawer, which can then be slid towards the back of the station, where the formwork is located.

Figure 36
Once a new layer of raw material is in the formwork, a wooden rammer is used for pre-compaction.

Figure 37
To fully compact the mass, a specially devel-oped machine repeat-edly drops four weights into the formwork.

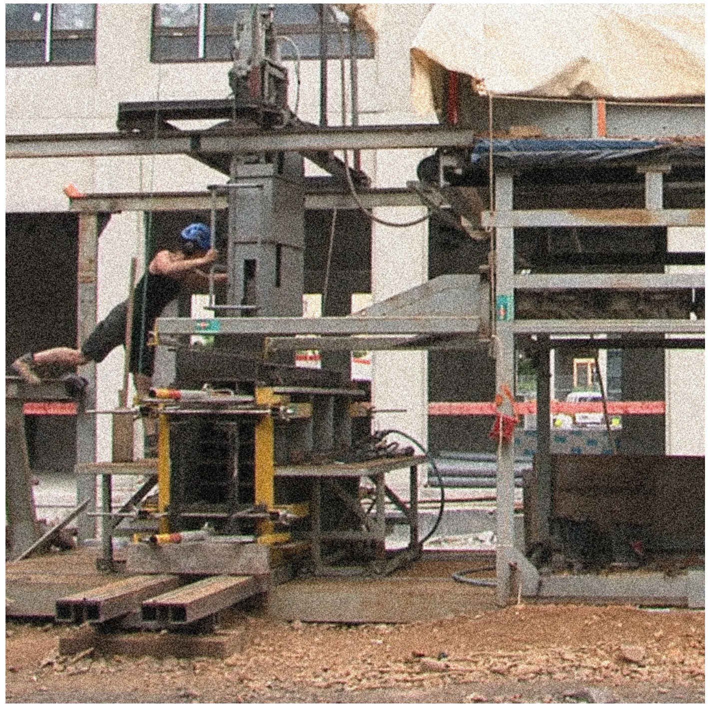


Figure 38
The compaction machine is positioned on tracks but has to be guided by a worker.

Figure 39
Threaded rods, which were rammed into the first layer of each element, are used to facilitate the transport.

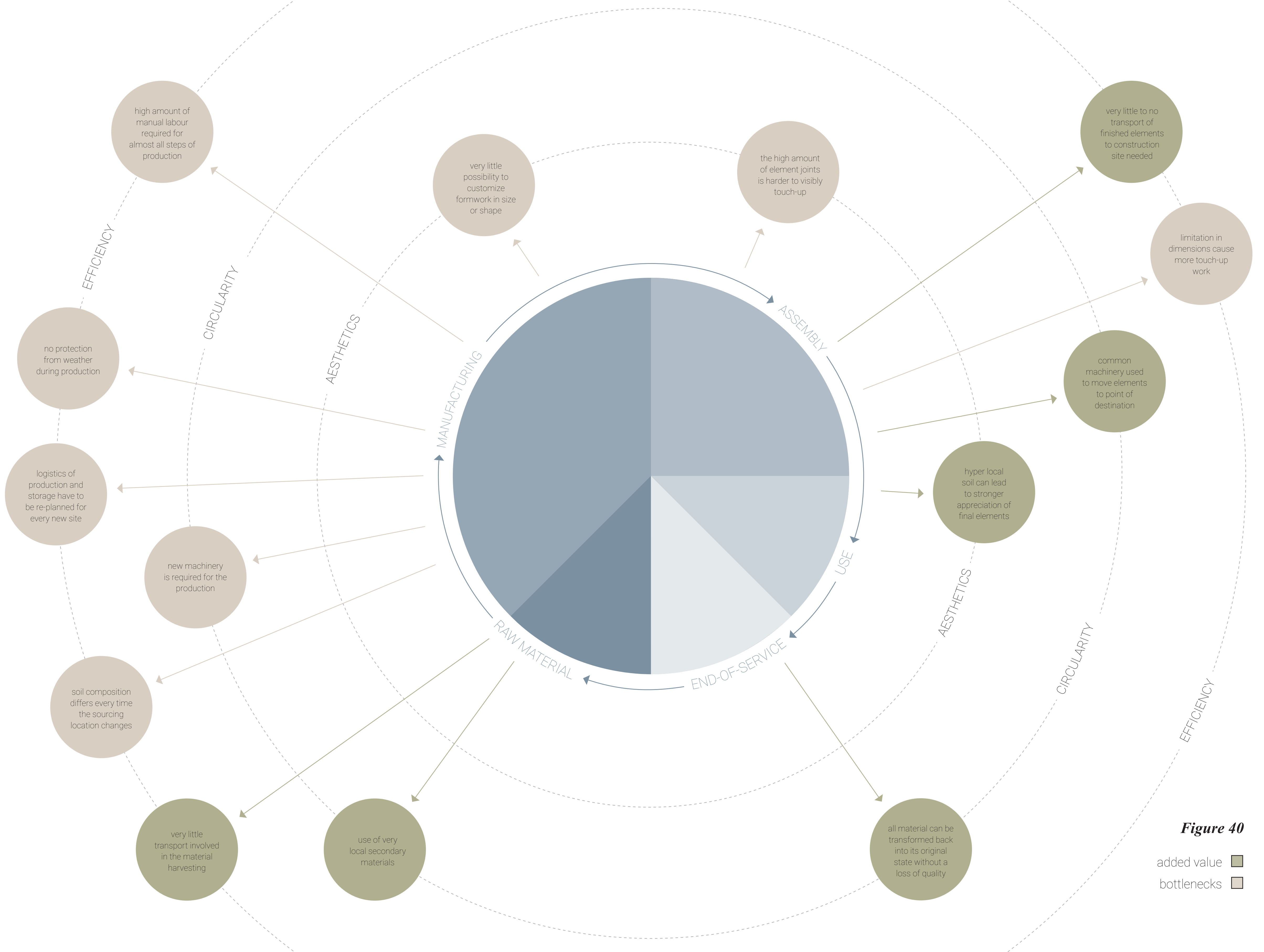

high amount of manual labour required for almost all steps of production
very little possibility to customize formwork in size or shape
the high amount of element joints is harder to visibly touch-up
very little to no transport of finished elements to construction site needed
limitation in dimensions cause more touch-up work
common machinery used to move elements to point of destination
hyper local soil can lead to stronger appreciation of final elements
no protection from weather during production
logistics of production and storage have to be re-planned for every new site
new machinery is required for the production
soil composition differs every time the sourcing location changes
very little transport involved in the material harvesting
use of very local secondary materials
all material can be transformed back into its original state without a loss of quality
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Figure 40

Pugh Matrix

Pugh Matrix

The identified values and bottlenecks from the case studies are collated in categories in Figure 41, to allow for a comparison. Reflecting upon the efficiency, Lehm Ton Erde scores the best, which is hardly surprising, considering that the full fabrication system and machinery are designed specifically for rammed earth, and raw material can be sourced locally and pre-filtered, resulting in a similarity of properties. The processes of Erne AG are very optimized towards automation too and have the advantage of a comparably simple and compact production line. For further projects, this can be set up at a shorter distance to the site, thus reducing transport distances. In that case, however, sourcing and testing of the raw material is more effortful due to changing availability and composition. The same applies to the fabrication station of Le Pisé, which, similarly to the “Roberta” of Lehm Ton Erde, is also conceptualized solely for rammed earth. Contrastingly though, due to the aspiration of maximum portability and independence of other infrastructure, like indoor fabrication halls, the efficiency is not comparable, and a high amount of manual labour is needed especially in the ramming process and for later touch-ups, due to small element sizes. The August Lücking semi-automated masonry unit scores with the possibility to produce comparably large individual elements, which reduces the efforts for manual touch-ups in the assembly stage. Furthermore, the very consistent properties of the raw material due to the direct extraction make large amounts of testing dispensable. However, many steps in fabrication depend on manual labour and processes are not optimised, presumably also because the current production is mostly focused on individual elements and not large quantities.

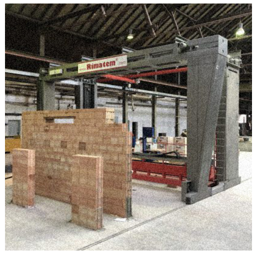
The key feature regarding aesthetics, which is influenced by the type of production, is

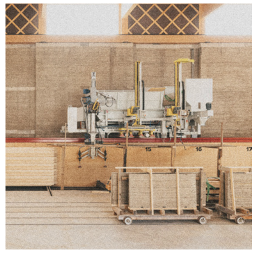
freedom in the size and shape of the resulting elements. Due to the design of the semi-automated masonry unit of August Lücking for full-size wall elements, also the dimensions of rammed earth elements can be quite large. However, the linear movement of the compaction plate predetermines a rectangular shape. The portable station of Le Pisé does allow for slightly more freedom due to the manual guidance of the compaction weights, and individual formwork of each element, but the element size is very limited. Complex forms can be realized most efficiently with the seven-axis robot of August Lücking, which allows for the highest range of movement, whilst having a fully automated compaction process. Lehm Ton Erde shows the lowest possibilities in customizability, being limited not only to a rectangular shape but also to a maximum element height of 120 centimetres. However, its 40-meter-long production line does allow for the longest horizontally continuous layers of rammed earth, which can be visually interesting for larger walls.

Due to the processing of rammed earth without additives in all case studies, the elements equally allow for circular use for their end-of-service scenario. Lehm Ton Erde, Erne AG and Le Pisé already include a circular approach in the acquisition of raw material by using secondary resources from landfills or construction sites, which is disregarded by August Lücking. Besides the rammed earth material itself, also resources employed for the infrastructure count towards the holistic consideration of circularity. In that respect, August Lücking sets an example by having almost no changes and additions to the already existing production line. Likewise, Erne AG makes use of its available infrastructure with only small adjustments. On the contrary Lehm Ton Erde uses a newly built production facility and specialized machinery, similar to Le Pisé.

Figure 41

Pugh Matrix





	August Lücking GmbH & Co. KG Warburg (DE)	Lehm Ton Erde Baukunst GmbH Schlins (AT)	ERNE AG Holzbau Laufenburg (CH)	Le Pisé Chambles (FR)
EFFICIENCY				
TRANSPORT OF RAW MATERIAL +1 There is very little to no transport. 0 Transport routes are kept to a minimum. -1 Transport routes are not kept to a minimum.	-1	0	+1	+1
COMPOSITION +2 There are almost standardized properties in each batch of raw materials. 0 There is a little variation in properties in each batch of raw materials. -2 There is a great variation in properties in each batch of raw materials.	+2	0	-2	-2
FORMWORK ASSEMBLY AND DISASSEMBLY +1 A mostly automated process is used. 0 A mix of manual labour and automated processes is used. -1 Most work is being done manually.	-1	0	0	-1
MATERIAL FEEDING +1 A mostly automated process is used. 0 A mix of manual labour and automated processes is used. -1 Most work is being done manually.	-1	+1	0	0
RAMMING PROCESS +2 A mostly automated process is used. 0 A mix of manual labour and automated processes is used. -2 Most work is being done manually.	0	+2	+2	-2

	August Lücking GmbH & Co. KG Warburg (DE)	Lehm Ton Erde Baukunst GmbH Schlins (AT)	ERNE AG Holzbau Laufenburg (CH)	Le Pisé Chambles (FR)
TRANSPORT OF ELEMENTS	0	-1	0	+1
TOUCH-UP WORK	+2	0	0	-2
SUBTOTAL	+1	+2	+1	-5

TRANSPORT OF ELEMENTS
+1 There is very little to no transport.
0 Transport routes are kept to a minimum.
-1 Transport routes are not kept to a minimum.

TOUCH-UP WORK
+2 Very little to no touch-up work is required.
0 Touch-up work is required only in horizontal or vertical direction.
-2 Touch-up work is required in horizontal and vertical direction.

AESTHETICS

	August Lücking GmbH & Co. KG Warburg (DE)	Lehm Ton Erde Baukunst GmbH Schlins (AT)	ERNE AG Holzbau Laufenburg (CH)	Le Pisé Chambles (FR)
FREEDOM IN DESIGN	0	-2	+2	0
UNITY IN LAYERS	0	+1	0	-1
SUBTOTAL	0	-1	+2	-1

FREEDOM IN DESIGN
+2 There is high customizability in formwork possible (high flexibility in size and shape).
0 There is medium customizability in formwork possible (flexibility in size or shape).
-2 There is low customizability in formwork possible (little flexibility in size and shape).

UNITY IN LAYERS
+1 Optically continuous rammed earth layers in very long walls are possible.
0 Optically continuous rammed earth layers in medium long walls are possible.
-1 Optically continuous rammed earth layers in only short walls are possible.

CIRCULARITY

	August Lücking GmbH & Co. KG Warburg (DE)	Lehm Ton Erde Baukunst GmbH Schlins (AT)	ERNE AG Holzbau Laufenburg (CH)	Le Pisé Chambles (FR)
RAW MARTERIAL	-2	+2	+2	+2
INFRASTRUCTURE FOR PRODUCTION	+2	-2	0	-2
END-OF-LIFE	+1	+1	+1	+1
SUBTOTAL	+1	+1	+3	+1
TOTAL	+2	+2	+6	-5

RAW MARTERIAL

+2 Mainly secondary resources from landfill / construction sites are used.
0 A mix of primary and secondary resources is used.
-2 Mainly primary resources, excavated just for rammed earth, are used.

INFRASTRUCTURE FOR PRODUCTION

+2 Mostly already existing and in use facilities, machinery, and tools are used.
0 Conventionally available facilities, machinery, and tools are used.
-2 Highly specialized facilities, machinery, and tools are used.

END-OF-LIFE

+1 The material can be fully recycled without a loss of quality.
0 The material can be partially recycled.
-1 The material can not be recycled.

Requirements for Residential Housing Blocks

Requirements for residential housing blocks

There is no rigid definition for suburban areas, however, taking the framework of Harris (2010, 27), there are three characteristics usually identified, which are a low density, a peripheral location, as well as a certain newness to the area, whereby the newness as a factor can be questioned according to more recent literature (Hesse and Siedentop 2018, 105). Mozas and Aurora classify suburban areas in relation to dwellings per hectare, indicating densities of below 50 to 100 dwellings per hectare as suburban and low-density urban zones (2004, 8).

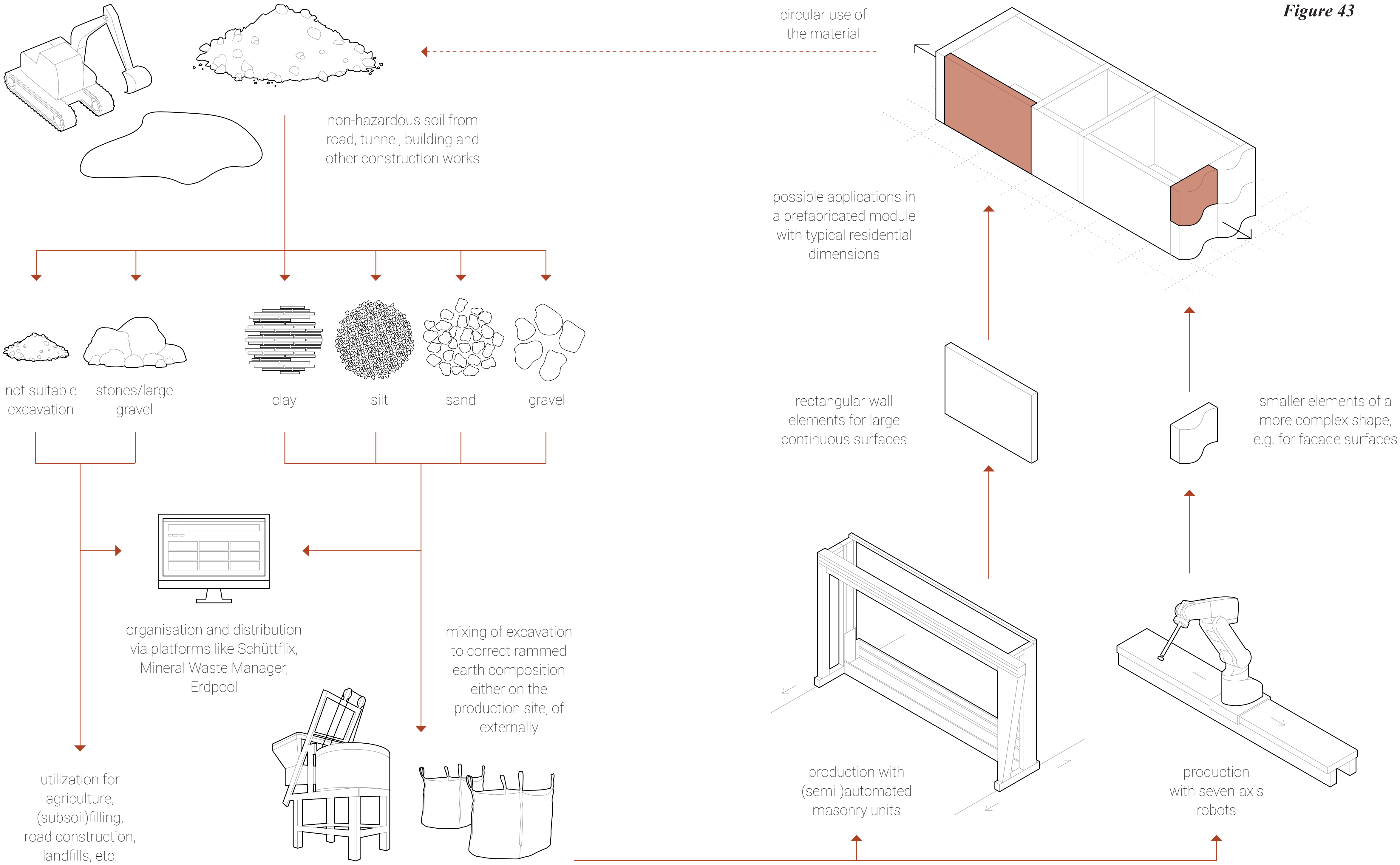
According to a listing of different building depth typologies, the most common building depths are found between 9 to 11 meters, whilst depths of 10 to 13 meters are a variation of that typology with larger unlit adjoining room zones in between two main rooms with a connection to daylight (Jocher and Loch 2012, 177). Very well-known typologies of that kind can also be found in already existing massive prefabrication structures, especially the so-called "Plattenbauten" as they can be found plentifully in post-war areas of the former East Germany, portraying a form of ultra-optimized residential housing. Building typologies from that time, like the "Wohnbauserie 70" were not only designed to allow for the most efficient mass production but also to optimize space within the dwellings and to allow for a variation of apartment sizes and layouts (see Figure 42). Within the strict grid size of 1,20 by 1,20 meters, the massive concrete elements have maximum dimensions of 6,00 by 2,80 for wall modules, and 3,60 x 3,00 meters for floor modules. Buildings characteristically have a depth of a tenfold of the grid size, thus 12 meters (Bundesministerium für Raumordnung, Bauwesen und Städtebau 1997, 7). Being often

criticized for its inflexibility, especially the typology "Wohnbauserie 70" generally exhibits great possibilities for individuality not only in its floorplans but also in the façade (DDR Museum, n.d.). Faller (1996, 215) also does not see its bad reputation in the system itself, but much more in its not reflected use with the main focus on mass production of always the same, in its bulk monotonous, building structures.

Figure 42
The model shows an exemplary floor plan of a building from the "Wohnbauserie 70".

4
conclusion

Figure 43



circular use of the material
non-hazardous soil from road, tunnel, building and other construction works
possible applications in a prefabricated module with typical residential dimensions
not suitable excavation
stones/large gravel
clay
silt
sand
gravel
rectangular wall elements for large continuous surfaces
smaller elements of a more complex shape, e.g. for facade surfaces
organisation and distribution via platforms like Schüttflix, Mineral Waste Manager, Erdpool
mixing of excavation to correct rammed earth composition either on the production site, of externally
utilization for agriculture, (subsoil)filling, road construction, landfills, etc.
production with (semi-)automated masonry units
production with seven-axis robots

conclusion

The analysis of the four case studies points out different values and bottlenecks which influence the efficiency, circularity, and aesthetics of the resulting rammed earth elements, as questioned in Q1

Concerning the efficiency in the production, especially the variety of raw material composition, and the required labour in the ramming process and touch-up works can be identified as decisive factors. Strategies can be seen in the involvement of external stakeholders, like local landfills or construction companies, which already prefilter material, and thus contribute to more uniformity of the rammed earth mixture. More recently emerging distribution and organization platforms, such as Schüttflix, Mineral Waste Manager, or Erdpool, represent an interface which can ease this process even further by classifying accruing mineral material and directing suitable charges. Even though the handling of primary soil extractions is the most efficient way towards consistent material quality, it does not present a valuable solution since it contradicts circular objectives. For the ramming process, the use of a seven-axis robot, like at Erne AG, as well as the specially developed "Roberta" from Lehm Ton Erde, present almost fully automated solutions for an otherwise very labour-intensive work. In a reduced-manner, this also applies to the utilization of semi-automated masonry units, as seen at August Lücking, which, however, still partly relies on manual compaction. On the other side, this way of production allows for maximised element sizes, thus reducing the necessary labour for later touch-ups of joints in the assembly phase. Concerning the portable station of Le Pisé, the bottlenecks regarding efficient production predominate. Due to very labour-intensive processes, the only value for efficiency lies in its

hyper-local approach. However, by using the masonry prefabrication infrastructure of other already existing companies, or by building up fabrication lines with commonly available and in-use seven-axis robots in suitable locations, at least regional production can be reached, as Figure 44 exemplarily depicts for Germany.

Next to enhancing the consistency of raw rammed earth material, the already-mentioned distribution and organization platforms for mineral materials can also contribute to circularity by enabling a much more barrier-free availability and thus, utilization of the mostly as waste denoted, non-hazardous soil excavations. Applying the term of circularity also on the infrastructure needed to produce the rammed earth elements, the systems of fabricating with semi-automated masonry units, as well as with seven-axis robots, are the most promising due to their wide availability, thus preventing the need to construct more specialized production sites.

Aesthetically, the most decisive factor that is influenced by the type of production is the design freedom in correlation to the customizability of formwork. The mostly linear fabrication systems seen at Lehm Ton Erde, Le Pisé and August Lücking are very limiting in shape, whilst, especially in the case of August Lücking, allowing for dimensional freedom. On the contrary, the robotic production at Erne AG offers opportunities for much customizability of formwork.

Applying the results to the use of the prefabricated rammed earth elements in a modular way that responds to requirements for housing purposes, as addressed in

Q2, the example of the "Wohnbauserie 70" shows that residential housing can be constructed with massive elements of maximum sizes of 6,00 by 2,80 metres for wall modules, and 3,60 x 3,00 meters for floor modules, whilst using a 1,20 by 1,20 meter basic grid. Fabrication with the semi-automated masonry unit allows for the making of elements which are similar in size to that, confirming that those dimensions are realizable in terms of transport, but also logical for floorplan layouts. Addressing the critique of the monotonous appearance of prefabrication with little room for customizability, the use of a 7-axis robot, especially for façade elements, can allow for more individual distinction amongst other buildings. Furthermore, different to the referred prefabrication movement, the aim is not to build arbitrarily and in large numbers, but to react to the respective location, not only in the façade but also in urban concepts and massing.

To conclude the guiding research question of how advancements in rammed earth prefabrication can allow for broader use of the material in multi-family residential buildings in the sub-urban Central European context, reference can be taken to the so-called chicken and egg problem, addressing the dilemma of declaring cause and effect of an occurrence (BC Materials 2023): On the one hand, the confined offer of non-conventional building products, like rammed earth, limits their wide use, creates mostly higher prices, and prevents a familiarity amongst professionals. On the other hand, the resulting reduced demand for those alternative building materials prevents companies from investing in the infrastructure necessary to scale up the production, push down prices, and thus allow for a broader application. Coordinating the product and the already existing infrastructure with one another can break this cycle, as illustrated by August Lücking. Without major investments, rammed earth elements are much more accessible for clients in their area now, whilst August Lücking can still use the full production capacity of machines and available labour with a mix of brick and rammed earth. Thus, the concluding diagram of the methods used in Figure 43 sets a focus on already existing infrastructure.

The investigation of different strategies for manufacturing rammed earth on a broader scale serves as an important and indispensable prerequisite for the design of the rammed earth housing system. The aspect of efficiency is crucial since the

product would otherwise have no real possibility of being available in the quantity needed and at different locations. Considering circularity as another factor comes naturally with the need to approach resources on a more efficient level to get closer to the set climate protection goals. Aesthetics eventually bridge the gap between industry and design by giving important indications of limitations related to each manufacturing method, which determine minimal and maximal dimensions of modules of the housing system, as well as possibilities to create a variation in shape. Parameters that are not influenced by the type of machinery used for the fabrication are colour, surface, and structural quality since they solely rely on the composition of the raw material, which is subject to natural fluctuations and thus requires special attention in the assorting process.

Eventually, rammed earth is not to be seen as the new concrete and mass product, but as an addition to the building material and product market, which could substitute for some currently used, non-sustainable building materials, whilst making use of the abundant resource soil excavation, thus enabling a more purposeful use of other, much more limited resources, to where they are truly needed.

Further research, especially in the design phase, can focus on representing the method of prefabrication in the appearance of rammed earth, since current methods mostly follow the objective of giving prefabricated walls a monolithic appearance, replicating the look of in-situ rammed walls rather than expressing their prefabricated properties. This can be combined with an exploration of methods of assembly, leading to new aesthetic concepts.

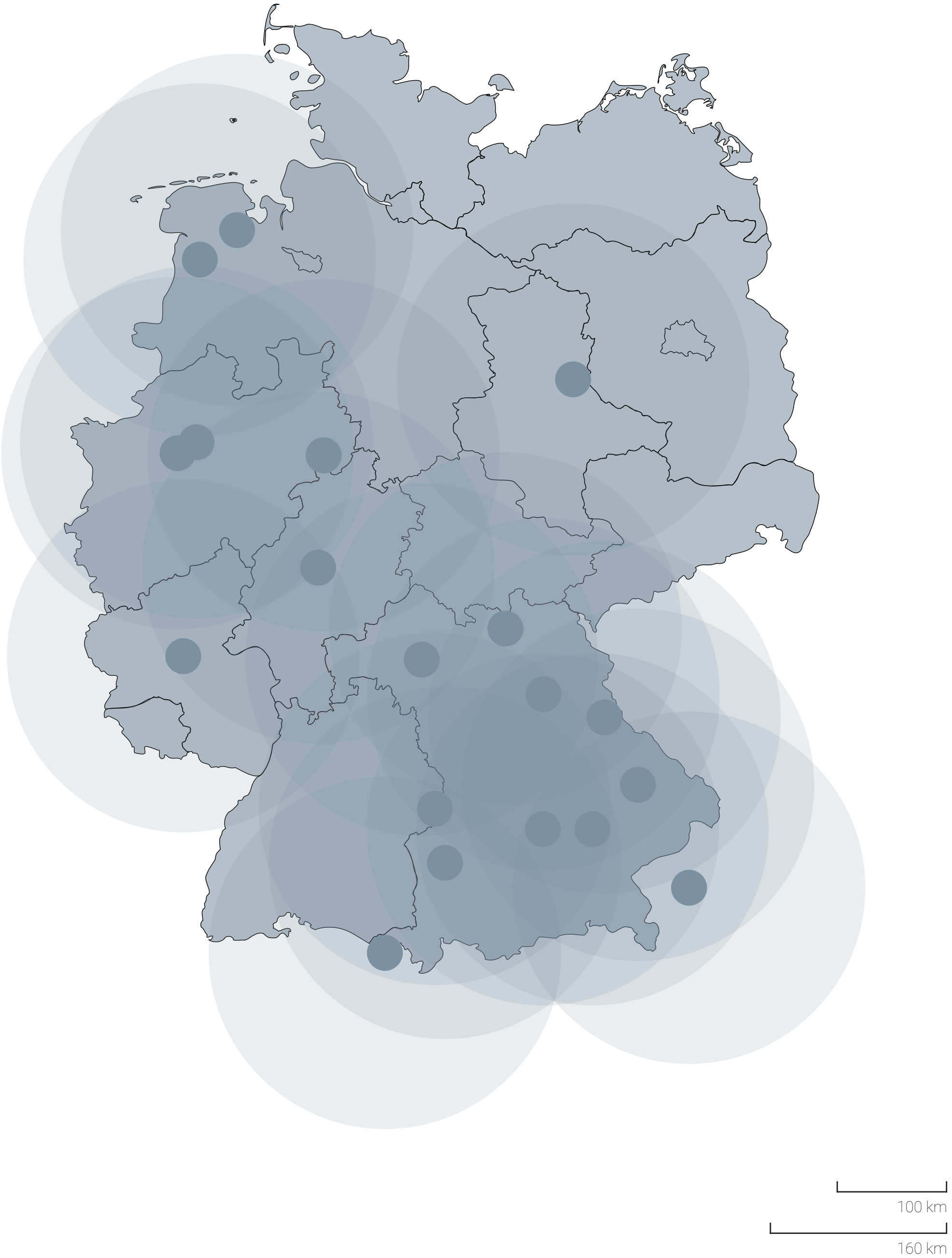


Figure 44

There is no clear definition for what makes a building product regional. However, referring to the LEED v4.1 standard, "products sourced (extracted, manufactured, purchased) within 100 miles (160 km) of the project site" (U.S. Green Building Council 2023, 96) are assessed more valuable. Applying this radius for already existing companies in Germany, which already posses prefabrication infrastructure for masonry elements, shows that, with exemption of the north-east, all areas of Germany are covered with possible production facilities for rammed earth.

appendix

appendix

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appendix

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