AM IN CONSTRUCTION: TAKING ENVIRONMENTAL SCALABILITY INTO CONSIDERATION

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Life-Cycle Assessment (LCA) of produced components and buildings growingly accompanies the development of Additive Manufacturing (AM) in construction. Considered a promising array of techniques to reduce the quantity of materials used, AM is however rarely evaluated from the perspective of the environmental impact of the machinery it mobilizes. The present research argues for a systematic evaluation of both the material and the machinery, demonstrating the variability and potential harmfulness of environmental impacts associated not only with the first, but also with the second. Reviewing different AM set-ups and discussing the amount of critical materials present in them as well as the consequences notably for abiotic depletion, ecotoxicity and human toxicity, the text concludes with a roadmap for sustainable AM in construction.

INTRODUCTION

Additive Manufacturing (AM) for the AEC industry has seen steady development in the past two decades, going from experimental practices to a growing market within this and other industries. However, neither for AM nor for digital fabrication processes at large is the environmental footprint of those innovative practices entirely known yet, including when use is made of these technologies in AEC. The state of the art in environmental assessments of these processes slowly develops as Life-Cycle Assessment (LCA) legislations come to pass and take more importance in the effort to reduce emissions associated with the built environment [1-5]. Recent legislation updates in Denmark, with the new carbon cap per built sqm, or in Europe at large, with the integration of maintenance and end-of-life guidelines in the new Construction Products Regulation, attest to the growing attention for sustainability in AEC [6,7].

In many cases, the assessments performed demonstrate the materials savings allowed by AM, yet the general claim for sustainability of these processes is weakened by the fact that a majority of studies maintain the traditional framework of LCA for built environment, neglecting to integrate machinery into the system for their assessments. From the machinery perspective, these processes nevertheless represent a significant shift from previous construction techniques, introducing many new high-tech tools whose footprint could be higher. This could change the balance traditionally in play in construction, where the materials impacts considerably outweigh those of the fabrication system. Currently available data indeed shows an extreme variability in environmental impacts across AM set-ups. From an energy consumption perspective alone, the costs can vary a hundredfold [8]. The weight of the fabrication system impacts in comparison to the material impacts assessed in existing literature can vary from 1% to 84% of the carbon footprint [2,9].

As efforts towards industrial scalability of AM processes for construction are pursued, environmental scalability must be taken into consideration, which entails both gathering further data on the complete impacts of these and developing models for transfer. The present research proposes an argument for the consideration of digital machinery impacts and suggests a roadmap to take it into account when planning the scale-up of AM processes at industrial level in AEC.

IMPACT TRANSFERS

Digitizing a low-tech industry

The AEC industry has been known for its low productivity [10], an issue which can be associated with a relatively low-tech framework for construction processes. Until recently, little to no automation in construction processes has been at work, and the development in the past two decades of new digital manufacturing techniques has not yet been followed by large scale adoption. The rise of AM in the last decade has indeed been intended as means to heighten productivity by transitioning to a higher-tech, digitized industry with automated construction processes. While such changes might succeed in rising productivity in AEC, they also introduce significant changes in the composition of the machinery employed for manufacturing. As higher tech systems are employed, the quantities of critical materials in the system are especially susceptible to augment.

Critical materials are defined as serving an essential function in manufacturing while having significant risks of supply disruptions [11]. They are used in components such as batteries, alloys, magnets, circuitry and integrated throughout all products of the digital chain. Lists of materials identified as critical vary according to sources, but include rare earth materials and battery minerals, as these are critical materials for energy (the “electric eighteen” - aluminium, cobalt, copper, dysprosium, electrical steel, fluorine, gallium, iridium, lithium, magnesium, natural graphite, neodymium, nickel, platinum, praseodymium, silicon, silicon carbide and terbium). While a strong focus is placed on their role in energy production, these materials are in general highly relevant to digital infrastructures as they are also used there.

More specifically in AM, critical materials can be found across all hardware components: motors, extruders, cables, robotic arms, controllers, etc. (Figure 1). These materials are not only critical in the sense that their supply chains are estimated as potentially endangered, rendering their fabrication, use and maintenance riskier. They are also responsible for increased human and environmental impacts in comparison to more conventional, lower-tech set-ups in construction, including higher abiotic depletion potential (or resource use) or higher human toxicity [4] - a second argument for their careful consideration in the development of AM for AEC.

From carbon emissions to abiotic depletion

Recent updates in legislation to consider the environmental impact of construction activities focus on two areas in particular. First, lowering the carbon footprint of the manufacturing phase, as the new EU policies aligning other countries with Denmark for a carbon cap per built sqm shows [7][12]. Second, lowering the energy consumption of the use phase, as the 2024 update of thermal regulations in France shows, imposing a 20% diminution [13]. A secondary focus is placed on energy consumption during construction, an indicator that has already raised attention in AM. Studies on Wire Arc Additive Manufacturing (WAAM) for example have shown the material savings that can be achieved with such techniques, but also the skyrocketing energy consumption associated with melting metallic materials needed in those processes [14]. Indicators mentioned above, which are particularly sensitive when resorting to critical materials intensive hardware set-ups in AM, are rarely considered. Yet existing studies show the increased impact AM techniques can have in these areas. As Figure 2 shows, large-scale robotic AM concrete set-ups are estimated to diminish the Global Warming Potential (GWP) of 1 sqm of wall by 30%, but they also multiply the Abiotic Depletion Potential (ADP) of 1 sqm of wall by 52 [4].

This illustrates the phenomenon called impact transfer, or burden shift. While a given fabrication technique or material might significantly better some of the indicators evaluated, it can also worsen other indicators, shifting the impacts from one part of the spectrum to another instead of representing a truly better solution for the use researched. The focus on specific indicators such as Global Warming Potential, as is seen in the AEC industry, tends to hide impact transfers that might be at play in AM. The WAAM and 3DCP examples given here, showing impact transfers in energy and abiotic depletion indicators, demonstrate the need to reconsider LCA for AM processes in AEC, evaluating hardware across the board of indicators to better map out the risk of impact transfers and associate damage to the environment.

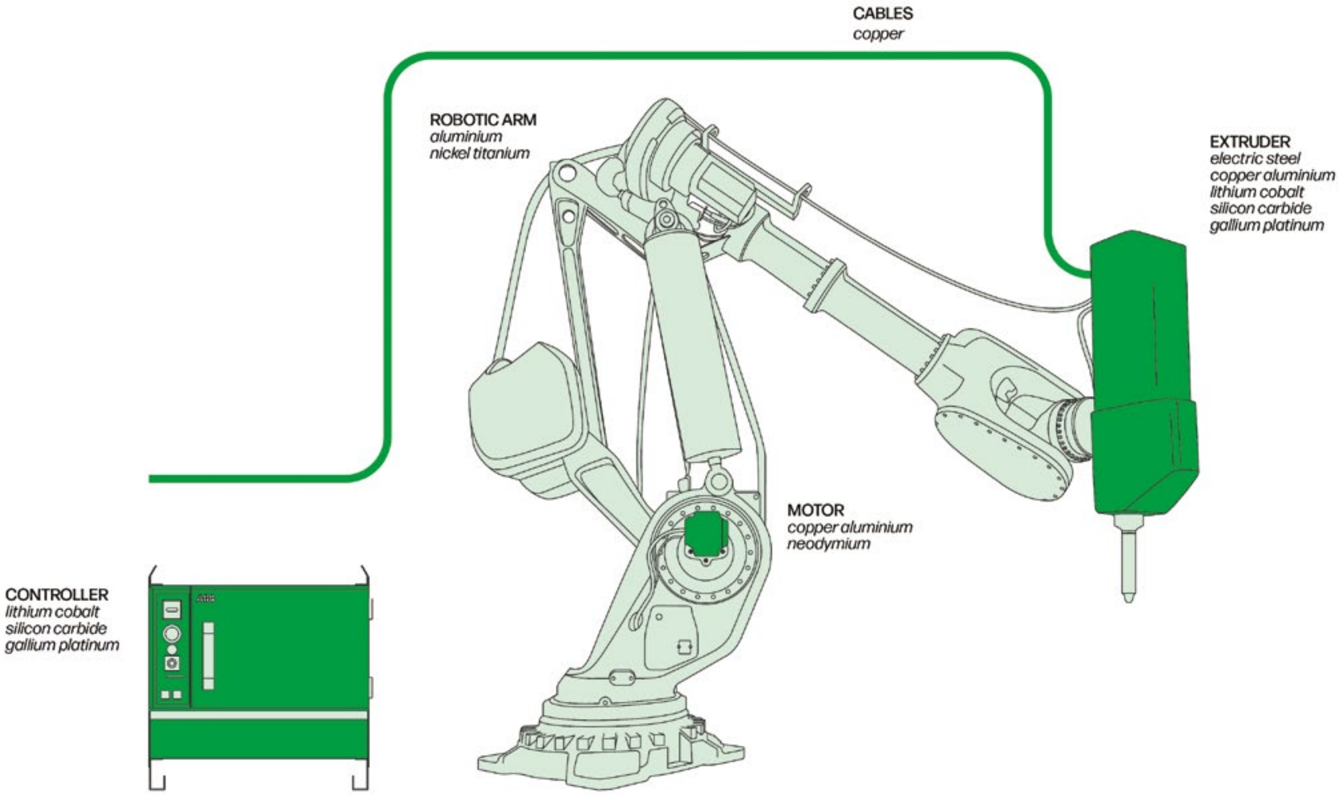

Figure 1: Critical materials presence in AM set-ups.

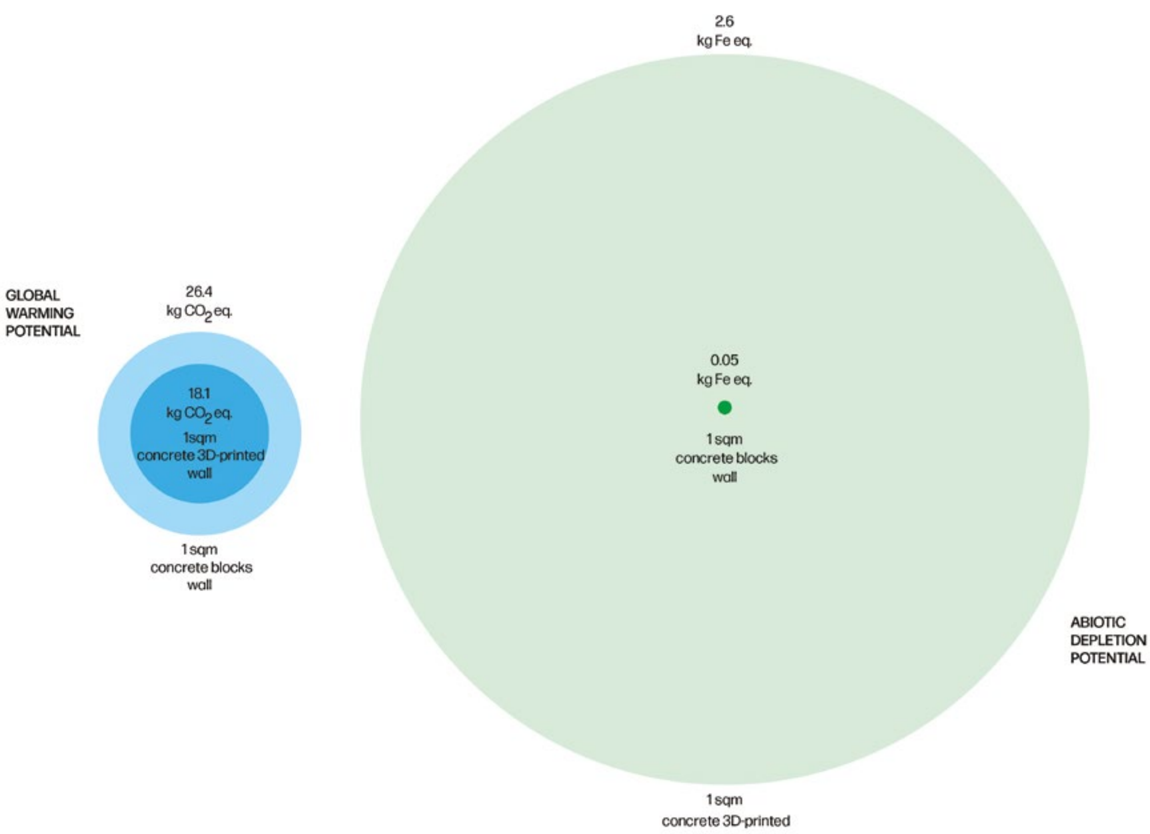

Figure 2: GWP and ADP of 1-sqm of concrete AM wall and of 1-sqm concrete block wall (data [4]; figure by the author).

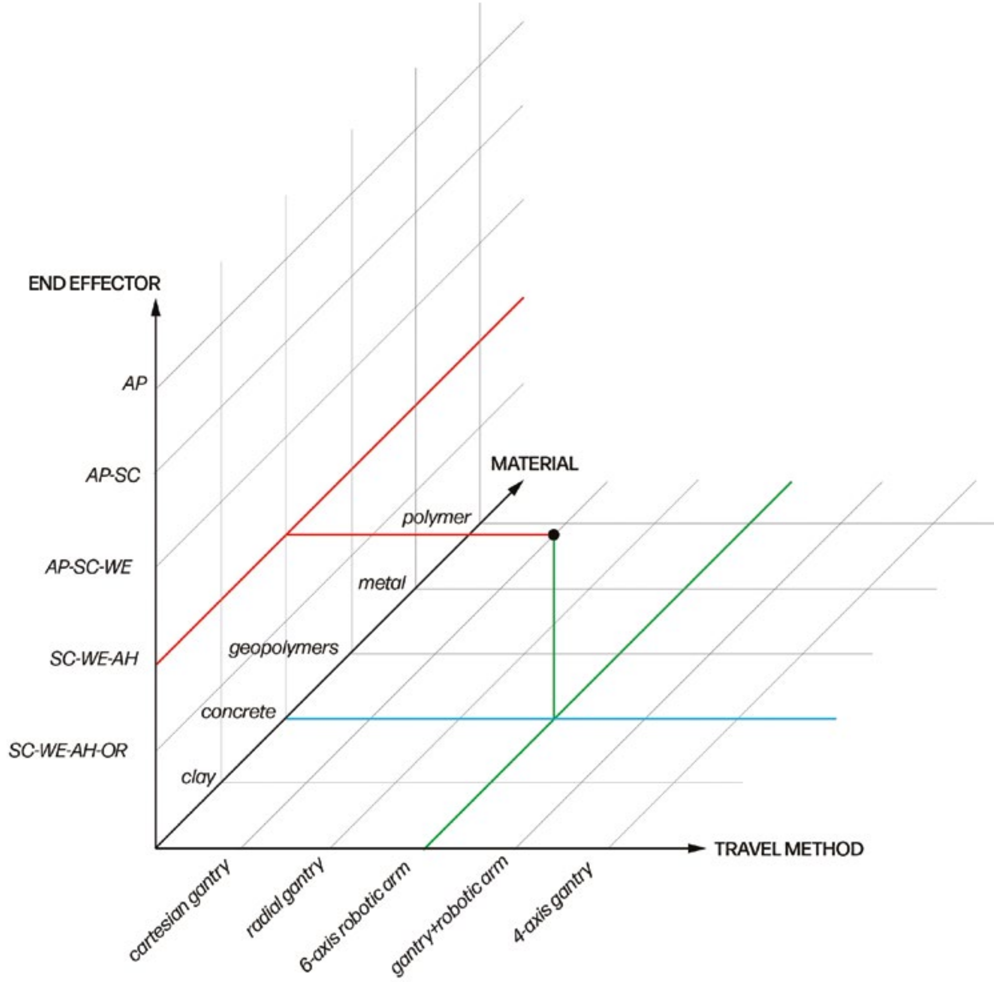

Figure 3: The MET matrix for AM.

A DATA MATRIX FOR SUSTAINABLE AM

Classification and overview

Of particular importance in this endeavour is the diversity of hardware set-ups in AM. This diversity entails the existence of set-ups that might be more sustainable than others, especially regarding the need for a lesser consumption of critical materials in their manufacturing. This means in turn that pathways exist to develop the resort to AM at industrial scale in AEC that could be significantly less damaging to the environment, as well as significantly more resilient to global geopolitical shifts. However, to select such set-ups and pathways, both extended data gathering and comparison strategies are needed.

Figure 3 presents a data matrix for sustainable AM, providing an overview of potential techniques. The matrix presents three axes: material used for printing (clay, geopolymer, concrete, etc) on one hand, and end effector (extruder or other, as well as characteristics such as air pressure feed, integrated additives mixing or wide extrusion) as well as travel method (gantry, robotic arm, cable robot, etc) framing the hardware on the other hand. Depending on the availability of techniques and the availability of an associated LCA, the matrix allows for mapping together both states of the art. Cases of techniques developed but not evaluated and cases of techniques not developed appearing in the matrix guide the effort in research. Cases of techniques not evaluated allow for a focus of the effort in data gathering to establish a comprehensive understanding of environmental impacts of AM. Cases of techniques not developed can be studied relying on the separate assessment of existing end effector and travel method, evaluating the environmental relevance of developments associated to such new AM possibilities. This creates for the matrix the potential to target lower impact systems that have not been developed yet but could become instrumental in the development of sustainable AM for AEC.

Balancing system and material footprint

As the example shown previously highlights, part of the impact transfers at play in resorting to AM happen between material and system. It is these particular impact transfers that current LCA practices for the built environment and their replication in higher tech set-ups are the least susceptible of detecting. To tackle this, the matrix presents two dimensions dedicated to the hardware and one dimension dedicated to the material. This allows for mapping LCA efforts in the domain according to the literature and enables a comparison between systems to study their balance between material and system footprints. This leads to the detection of set-ups that present a good balance and therefore are the most susceptible of being scaled up with lesser environmental damage.

Travel method evaluation

From the three dimensions of the proposed AM matrix, the present paper focuses on the travel method evaluation. As has been highlighted earlier, materials for AM and their environmental impacts are already the topic of numerous studies providing relevant data to grasp their role in the system [1,2,4,5,15]. For smaller impact materials already identified - clay, geopolymer and potentially low carbon concrete -, scalability necessitates the replicability of printability and stakeholders to produce the material, which are not at stake in the present discussion. Regarding the end effector, environmental scalability issues could be tackled both in the diversity of end effector types and in the adaptation of parameters such as print speed flow rates, which existing studies hint toward having an impact [16].

However the present research focuses on scalability issues from the travel method perspective, which provides insights into the strongest disparities across the board and therefore constitutes an emblematic case study of environmental issues to be tackled within AM. One of the major challenges in AM for construction is the issue of scale. As buildings are the production aim, a constant concern is the study and selection of strategies to reach such size within the production workflow. There are several approaches to this. One consists in scaling up the system to increase the work area and therefore manufacture products at the size of construction products typically in use or even scale up the work area enough to print an entire building. We focus here on the analysis of the impacts at stake with such scaling up strategies.

EQUIPMENT SCALES AT STAKE

Linear impacts

The first series of impacts highlighted by the study of AM travel methods and their specific environmental footprint is that of linear impacts. These follow the increase in size of the printer in a proportional manner. Cartesian AM systems relying on gantries as travel method provide an example of this. The low impacts of the printer itself in the case of small scale cartesian systems of desk printers have already been demonstrated [1]. Larger scale set-ups constitute a larger however similar version of these systems.

Such gantries are instrumental to scale-up strategies aiming at reaching a building size print area. The largest of such cartesian systems however introduce impacts in relation to the foundations necessary to implement them, as the COBOD cartesian printer model BOD2 shows. Further impacts in cartesian systems for AM depend on the end effector used and on the inclusion of sensors to guide printing. Variability can also be introduced by combining a gantry with a second travel method, as can be the case placing a robotic arm on it in some set-ups [17]. These impacts are not subject to linear evolution within the scale-up and must be examined separately.

Exponential impacts

Robotic 6-axis arms used as a travel method demonstrate the presence of both linear and exponential impacts. Linear impacts are visible in Figure 4 within the different ABB IRB model series: small increases in reach result in small increases of the overall weight of the system, and in small increases of the presence of stainless steel. This is due to a linear increase in the neck length of the robotic arms which allow for such reach gains.

However, Figure 4 also shows jumps in the overall weight of the system from one model of robotic arm to the other. This is due to changes in the morphology of the arm associated with the difference in use intent, which is reflected in the design. As an example, the IRB 4600 series (reach 2.05-2.55m, payload 20-60kg) is designed by ABB for arc welding, assembly, material handling, machine tending and dispensing, while the IRB 8700 (reach 3.50-4.05m, payload 550-800kg) is designed for heavy-handling tasks such as vehicle chassis manipulation. This results, for the latter model, in the presence of a counterweight and extension significantly increasing the amount of stainless steel in the structure. This combined with the length of copper cables necessary for 3DCP with this model and the presence of several critical materials within the controller results in the increase in abiotic depletion potential and the associated impact transfer presented in section 1. Another example in change of design is given in the Kuka KR 40 PA model, designed for paletting with a reach of 2.1m and payload of 40kg, and with a frame of aluminium and carbon-fibre-reinforced plastic arms, altering the impacts associated with its manufacturing.

While the critical materials present in the controller and pendant are constant and only represent a significant jump compared to traditional, low-tech AEC techniques, the critical materials in motors can also induce jumps in the amount of critical materials present in the system when increasing the reach. The variation of motor sizes and associated critical materials content evolution also follows reach, still considering the ABB IRB series. ABB's approach to motor manufacturing as well as replacement within such robotic equipment entails that the impact evolves with jumps rather than in a linear fashion. Similarly cable lengths in industrial off the shelf AM systems come in different sizes and trigger jumps in impacts.

As well as changes in morphology which trigger differences in critical materials composition, the different purposes entail jumps in other chemicals. As an example coatings for the ABB IRB Foundry Plus 2 option, which are used to protect the machinery from harsh environments (for example 3DCP - see the evaluation of the XtreeE 3DCP set-up in [4]), contain nickel, aluminum and silicon and might also change the totals for impacts associated with the production of such materials. This as well as changes in polymer amounts used leads to potential impact increases and transfers not just for abiotic depletion but also human and environmental toxicity [18].

Cell weight per scale of set-up

While it is instrumental to keep track of the amount of critical materials present in the system, it is equally crucial to keep track of the weight of the system's environmental impacts within a larger LCA boundary also accounting for material. As one of the issues at stake is the question of whether traditional LCA assumptions for the built environment still hold when turning to AM and other digital manufacturing processes, balancing system with material impacts is key. The inventory of critical materials contents within a given system allows one to understand linear and exponential impacts and to direct the choice of hardware accordingly. However this is to be balanced with the importance that the hardware actually takes in a complete LCA looking at construction product impacts. While the exponential impacts associated to the scale-up of certain parts of the systems indicates that larger scale set-ups might be significantly more damageable to the environment, this remains to balance out with the type of material that such systems allow to process, which could potentially represent enough environmental savings to compensate the costs of a high-tech equipment.

Figure 5 shows the cell weight in comparison to the material weight within an LCA system evaluating a construction product or similar as a functional unit. It demonstrates the percentage of the environmental impact that the AM system in itself is responsible for. In cases where the system is subject to significant impact jumps when scaling up but only represents a fraction of the total impacts, the material being responsible for a larger part, the impact jumps within the system might potentially be negligible - as could be the case with earth 3D printing. In other cases the systems would be typically avoided in industrial scale-ups for AEC, as they might represent some of the most damageable options for the environment. In general the data presented shows that scale-ups in the system size do not only increase the amount of critical materials, it also increase the weight of the system in comparison to the weight of the materials. This points to the importance of exponential impacts

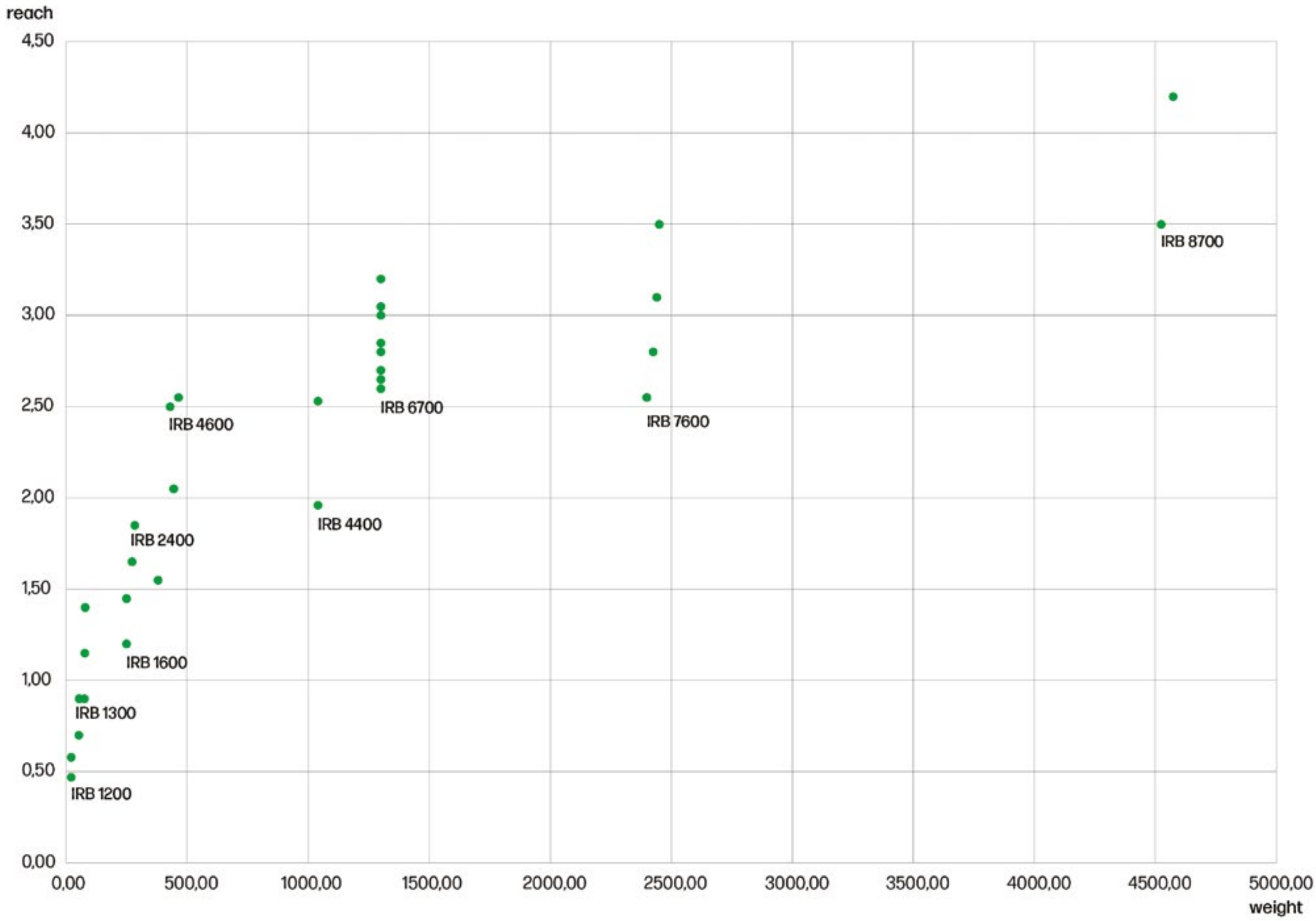

Figure 4: Weight evolution in ABB IRB robotic arms.

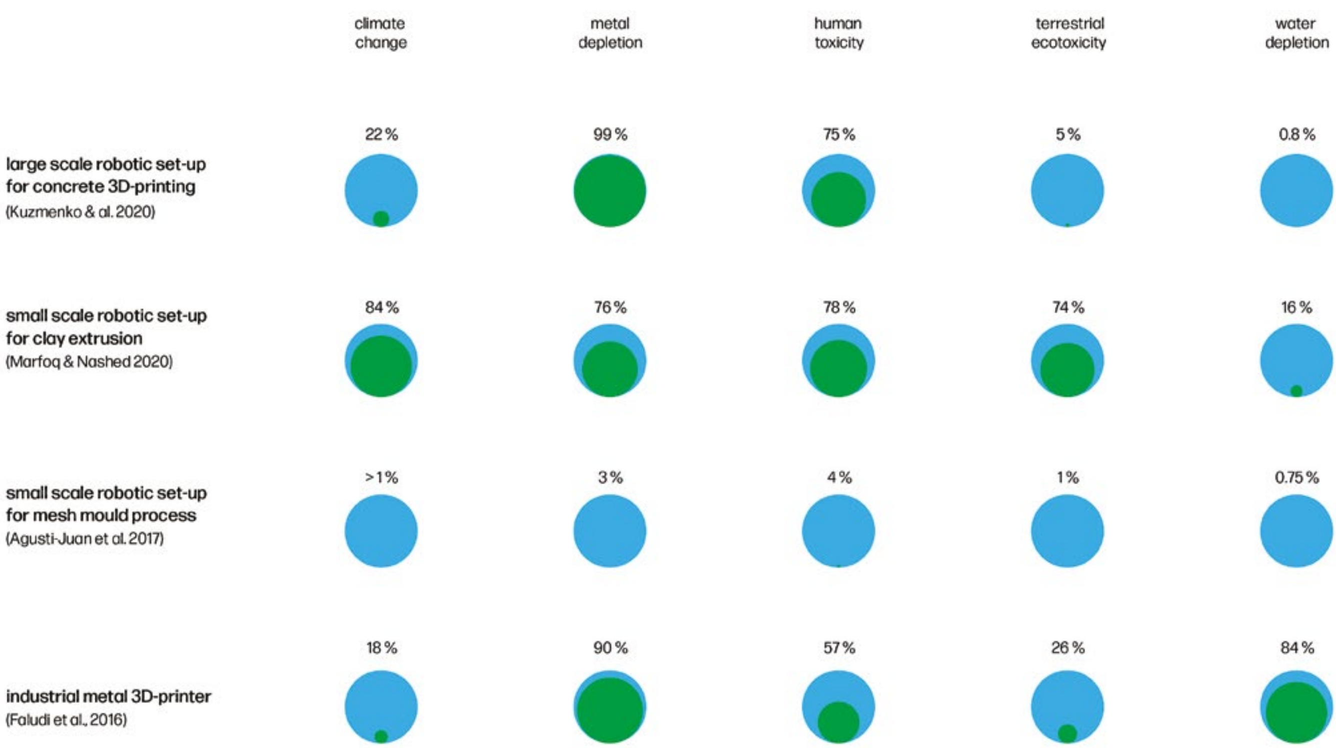

Figure 5: Set-up weight according to different scales and material AM set-ups - in blue the material and in green the machinery.

identified above. However, as with other considerations it shows the variability of environmental impacts depending on the specific AM set-up adopted, and corroborates the hypothesis of possible choices within AM techniques of more sustainable systems than others.

PRODUCTION SCALES AT STAKE

Outlays: modelling production capacities and their environmental consequences

To understand the role played by the set-up and how to allocate the impacts of producing the machinery across the construction products (or tonne of printed material processed), outlays must be modelled. Outlays define the amount of functional unit that can be produced with a given equipment, dividing the environmental costs of the equipment by as many functional units produced.

To model this, the use of the equipment during its lifetime must be calculated, taking into account maintenance time and work hours of persons operating the equipment, but also potential shifts in demand, especially with AM for AEC where the demand is currently often highly custom. The data presented in Figure 6 shows the variation in impact allocation depending on production strategies and resulting outlays, with up to 50% increase in production capacity and an associated decrease in impact allocation.

Outlays can be modelled on existing production rhythms but also on projected production rhythms for prospective / ex-ante LCA practices. This makes such models highly relevant in creating, assessing and adjusting industrial scale-up scenarios for AM in AEC. This is particularly the case presently as AM companies just start augmenting their production to a full-scale practice.

End-of-life and recycling of critical materials

Outlays allow modeling the allocation of impacts to ensure critical materials in the AM system do not represent too strong environmental pressure. However these impacts are associated with extraction of critical materials [18]. This entails that once the critical materials are extracted, their recycling can allow for more sustainable yet still high-tech practices for AM. This would also enable tackling issues of supply risk for critical materials. Figure 7 shows the level of supply risk faced by critical materials, with those present in AM systems highlighted.

These supply risks are associated with geopolitical pressures on logistical chains, but also to the sheer availability of materials, as the example table for copper shows below. The table furthermore identifies three levels of risk, depending on the feasibility of accessing and exploiting different parts of the global copper reserve.

Typology	Description	Amount (Mt)
Proven reserve	Proven, cost-effective technology	770
Possible reserve	Geologically identified, technically possible but may not be profitable	2720
Ultimate resource	Geologically identified but technically and economically uncertain	5600

Table 1: Copper availability [19].

The supply risk puts heightened focus on our ability to recycle critical materials present in AM systems, but also on our ability to project the use of the known reserves. As an example, studies have been performed on car batteries and their availability in regard to the critical materials reserves [19]. Authors of the study hint at the need to decide what amount of these reserves to direct towards electric cars, how many electrical cars this would represent and how the attribution of these cars could be performed should not enough critical materials be available to provide a car per person on the planet. Similar studies could help determine, depending on the impacts of specific AM set-ups, what amount of global critical materials reserves should be dedicated to AM machinery, and in turn what type of production it would represent in terms of construction products, as well as where in a building and in the world such products would be best used.

Establishing thresholds for industrial production scenarios

A third tool to model industrial production scenarios for AM in AEC that would remain within reasonable environmental impacts is the establishment of sustainability thresholds. This has been proposed already for material choices in AM. LCA of biopolymer AM has shown that despite enabling the use of certain waste flows in architectural uses, biopolymer recipes need to combine these waste flows with much more damageable binders in order to render them printable [5]. However recipes can be defined by identifying a printability threshold quantifying the minimum amount of binder necessary to ensure that the biopolymer can be processed by a 3D-printer as well as a sustainability threshold quantifying the maximum amount of binder possible while remaining under a certain GWP/kg cap. The biopolymer assessed in the study is shown to in fact be part of a larger range of recipes declinations [20], of which the combination of the printability and sustainability thresholds allows one to choose from guaranteeing the minimization of environmental impacts.

In a similar manner, abiotic depletion thresholds can be defined for AM set-ups. Such thresholds enable to model maximums that consider both advantages – processing

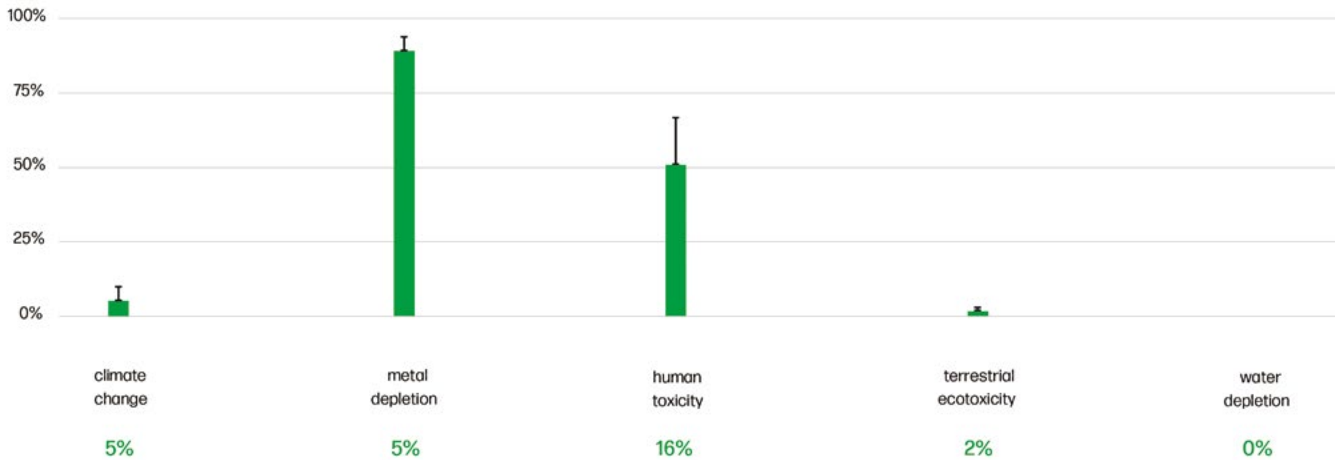

Figure 6: Outlay variation according to different production scenarios (data [4]; figure by the author).

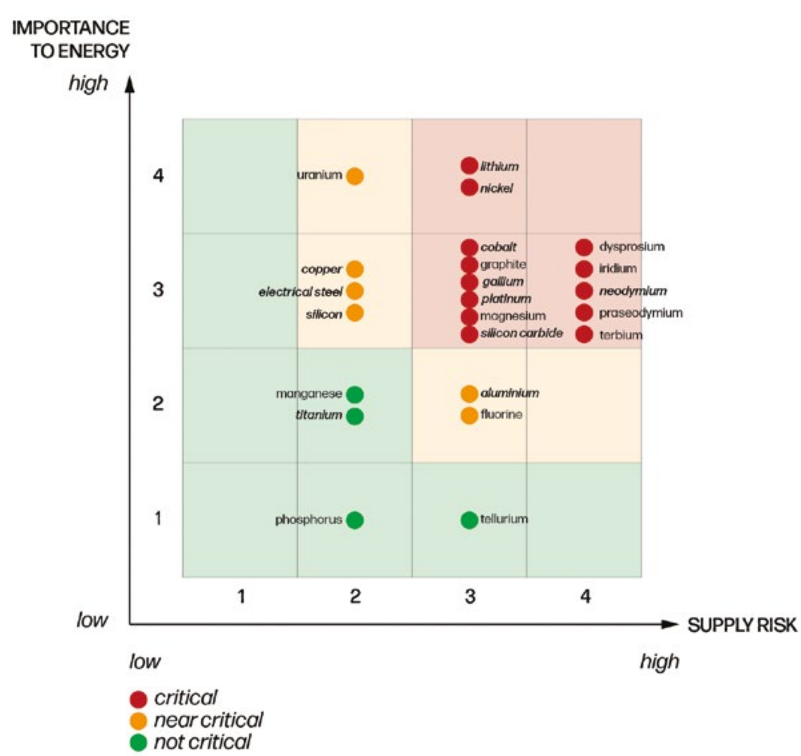

Figure 7: Supply risk table 2025-2035 [11].

new low impact materials - and downsides – higher impact set-ups –, as well as trade-offs which must be taken into account – higher fraction of the impacts for the system but an overall lower impact than alternative construction processes – of AM. This latter aspect raises the issue of favoring either the least damageable of two options or favoring a truly sustainable option - the thresholds are precisely designed to ensure the second approach, a need for guaranteeing more sustainable practices at large.

CONCLUSION

The present study discusses the sustainability of AM in AEC from a machinery perspective, demonstrating the importance of taking into consideration high-tech set-ups themselves to ensure an industrial development for the field that is compatible with environmental boundaries. It shows the ability of AM to navigate across a large range of impacts, and the possibility to choose amongst various set-ups and strategies to avoid the most damageable options. The study notably reveals the increases in impact associated with scaling up the systems and therefore the work area. Consequently, printing small is identified as a key development strategy for AM, privileging small-scale and low-impact set-ups that could also favor design for disassembly practices for 3D-printed component design.

Examining in greater detail the set-ups developed for component printing brings to light further choices. Gantries assessed here are designed for the end effector to travel across the printing bed, yet other options exist combining a static gantry with a moving bed. While only usable when manufacturing components, upon closer assessment such alternatives might reveal possibilities to limit exponential impacts and therefore represent venues of further development. In a larger perspective, considerations on on-site and off-site manufacturing bring to light issues of machinery design, and observations made in the present research on robotic morphology indicates that beyond AM strategies on construction scale themselves, complementary design directions exist for further research.

The study also offers methods of modelling production pathways as well as leads to further the study of impacts of AM in AEC, beyond the scale of the travel method employed. The matrix proposed might be extended with other criteria depending on the balance to be assessed, extended with other set-ups depending on the state of the art. The set of tools for production pathways modelling - outlays, end-of-life, thresholds - could be applied to set-ups identified in the matrix to understand their conditions of scale-up within environmental boundaries.

ACKNOWLEDGMENTS

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