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ASSESSMENT OF ADDITIVE AND CONVENTIONAL MANUFACTURING: CASE STUDIES FROM THE AEC INDUSTRY

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Given the development of Additive Manufacturing (AM), popularly known as 3D Printing, the coexistence of AM and conventional manufacturing (CM) in AEC will be a reality for the foreseeable future. Case studies on two AM metallic building components demonstrated that AM for building components is technologically feasible but cost-prohibitive today, and, in some cases, has lower environmental impacts than CM. Firstly, a feasibility study was conducted to assess the applicability, time to manufacture, and manufacturing cost of AM vs. CM of specific metallic building components. Secondly, Life Cycle Assessment (LCA) was used to assess environmental impacts of AM and CM for those two cases. The case studies were the first well-documented comparative analyses of AM vs. CM for building components, and they contribute to the emerging "AM-in-AEC" knowledge base with their assessment approach, findings and documented baseline efforts for the analyses. The studies also revealed that AEC practitioners lack a systematic way to rapidly and consistently assess the applicability (A), schedule (S), environmental impacts (E), and cost (C) of AM compared with CM to produce building components. Future work includes formalization of such an ASEC multi-criteria framework and impact assessment of the formalized assessment process on the effort and the consistency of the assessment between different assessors.

Keywords: 3D printing, Metallic building components, Applicability, Schedule, Environmental impacts, LCA, Manufacturing cost.

1 OBSERVED PROBLEM

The Architecture-Engineering-Construction (AEC) industry is becoming aware of the benefits that Additive Manufacturing (AM) technologies, popularly known as 3D Printing, offer (Khoshnevis 2004, Belezina 2012, Strauss 2013, Mrazovic 2014, 2015a, 2015b,) like just-in-time deliveries and mass-production of custom parts. Nonetheless, currently, AM technologies are not applied in AEC because of their lack of technological maturity (challenges in materials, technology, and production) (Strauss 2013), high manufacturing costs (Mrazovic 2015a), and lack of information about the value of AM to AEC practitioners (Mrazovic 2015b). Although the state-of-the-art of AM (Gibson *et al.* 2010, Stucker 2012, Mrazovic 2014) shows that the coexistence of AM and conventional manufacturing (CM) is a reality today, AEC practitioners have no systematic means to evaluate the choice between AM and CM to manufacture building components in a timely manner.

Literature review (Atkins Project 2012, Strauss 2013, Wang and Simkin 2015) and interviews carried out with 17 AEC practitioners revealed anecdotal and partial stories about the value of AM in AEC. A few isolated prototypes (Khoshnevis 2004, Belezina 2012, Strauss 2013) do not provide answers about how and if an AM technology should be applied on a specific AEC project. Furthermore, most of the data and assessment examples that have been published (Atkins Project 2012) focus on consumer products, i.e., products that are not at the geometric size scale of many building products. Finally, there is a lack of formal methods to assess AM versus CM for producing building components, and a study to assess the impact of such a formal method on the effort and the consistency of the assessment.

Motivated by the observed problems, the authors conducted a well-documented comparative analysis of AM vs. CM for making specific building components. This paper describes developed and conducted case studies with their methods and the results.

2 CASE STUDIES

To assess the potential value and feasibility of the research and determine the availability of data, two rounds of case studies were conducted to answer the following questions: Do AM technologies have value for the AEC industry? How to compare AM and CM for making building components? What are the criteria, datasets (input and output), and methods to compare AM and CM for making building components? What is the effort to do the assessment? Firstly, Mrazovic (2015a) developed and conducted a feasibility study to assess the applicability, time to manufacture, and manufacturing cost of AM vs. CM of specific metallic building components. In a second phase of the case study research, Life Cycle Assessment (LCA) (ISO 14040 Standards, 2006) and manufacturing cost analyses were used to assess environmental impacts and costs of the building components produced with AM and CM used as cases in the Feasibility Study.

2.1 Feasibility Study

To gain access to realistic and current industry data, knowledge and situations, the Feasibility Study was developed and conducted in collaboration with the R&D group of a global curtain wall contractor to evaluate the applicability, costs, and duration of the AM process, compared with CM, for two curtain wall components. In the first case, the authors explored the use of design optimization informed by AM capabilities to improve the structural performance of a metallic bracket, a plate that transfers loads from the curtain wall system onto the primary slab structure. The bracket was optimized to resist wind loads, absorb blast energy, dissipate earthquake loads, and dampen extreme wind. The current monolithic and heavy design was changed into a design that is light-weight and higher-performing, by including lattices that can be manufactured only with AM technologies. In the second case, AM technologies were analyzed to produce a large-scale curtain wall component, specifically a one-story metallic frame, as a single element on a construction site to eliminate the cost of extrusion, assembly, transportation, and packaging.

The assessment in the study started with the applicability analysis including three research steps:

(1) Identify the state-of-the-art of AM and the AM technologies and manufacturers relevant to building component production (based on the required material type and geometric constraints of the analyzed component);

(2) Gather and structure information about producing the specific curtain wall frames using CM;

(3) Collect information about the cost, time, and energy consumption for manufacturing the curtain wall frames using AM, by developing a questionnaire, and conducting semi-structured interviews with employees and CEOs of relevant AM machine manufacturers.

The schedule and cost were calculated and analyzed in the following research steps:

(4) Calculate the specific manufacturing schedule and costs by using the data collected and the data available from previous scientific research (Atkins Report 2012, Baumers e*t al.* 2010, Baumers 2012, Ruffo *et al.* 2006, Stucker 2012)

(5) Comparatively analyze supply chain costs; and

(6) Provide guidelines and recommendations to an AEC user, in this case about metallic AM.

The Feasibility Study showed that AM of metallic building components is technologically feasible, but is cost-prohibitive today. AM technologies with small-scale platforms, like EOS and Arcam, are suitable for AM of building components in size that fit in their build chambers, like the bracket from the study, but are not applicable for AM of large-scale building components. It is currently infeasible to enlarge their build chambers from approx. 300 mm to 4,000 mm because of the current speed, resolution and consequently the cost of deposition. The cost comparison between the CM and the AM of the aluminum curtain wall frame manufactured with small-scale platforms (EOS and Arcam), and large-scale metallic deposition technologies, produced by Sciaky Inc., DM3D, Optomec and Fabrisonic, showed that the large-scale technologies could be developed to manufacture building components of the analyzed frame size. The investment to prototype these systems would be between 1.6 and 4 million euros. The specific manufacturing cost to AM the frame using such a technology is mainly influenced by the processing speed and totals approx. 5,000€ (900€/m2 of building facade), where 30% of the calculated cost comes from material cost and 70% from AM, including processing and all post-processing, e.g., CNC machining, polishing, surface cleaning, etc.

2.2 LCAs of the Two Cases from the Feasibility Study

After the Feasibility Study, Mrazovic (2015b) oversaw two groups of Stanford students applying the ISO 14040 LCA (2006) methodology to analyze the environmental impacts of AM vs. CM of the two metallic building components from the Feasibility Study. These process-based LCA analyses included environmental impacts, costs, and sensitivity analyses. The software SimaPro was used to carry out the LCA analysis because it generates outputs like Global Warming Potential (GWP) in kg CO_2e emitted and abiotic depletion of fossil fuels in MJ. Cost analyses focused on the manufacturing phase. Mrazovic tracked the assessment process by documenting the duration of each step and the challenges students encountered, e.g., missing data, multiple ways to interpret gathered data, and validity of data sources. These challenges could lead to inconsistencies in the assessment process if repeated without a formal method. Two LCA studies (Arnstein *et al.* 2015, Gandini *et al.* 2015) demonstrated that the AM methods produce lower environmental impacts than CM in some cases for the same component, while the AM cost is greater than the CM cost (Table 1), especially if one wants to maintain the same schedule duration.

Table 1. Selected results from the case studies for the metallic bracket.

CATEGORY	CM	AM
Technology Applicability	✓	✓
Schedule (time to manufacture)	**2h**	**5-17h**
Environmental impacts (here shown greenhouse gas (GHG) emissions in kg CO_2e)	**131 (Steel) – 141 (Aluminum)**	**25-55 (Aluminum); 18-47 (Steel)**
Costs	**$95**	**$411-$1,064**

The bracket LCA showed that the environmental impacts of AM are at least 40% lower than CM (Figure 1, 2): AM consumes less water and energy than CM, and there are fewer human health, ozone layer, and acidification impacts. Three production methods were analyzed: one CM method, and two AM technologies, direct metal laser sintering (DMLS) and electron beam melting (EBM), in two material types, aluminum and steel. The results show that aluminum brackets have greater greenhouse gas (GHG) emissions, consume more energy, and require less water consumption than steel brackets throughout their life cycle. Analyzed AM cost of the bracket is 4 to 10 times greater than CM. As the greatest environmental impacts come from the raw material processing (in AM and CM), the impacts could be potentially reduced by decreasing initial mass of a component (e.g., through optimization) rather than locally sourcing material.

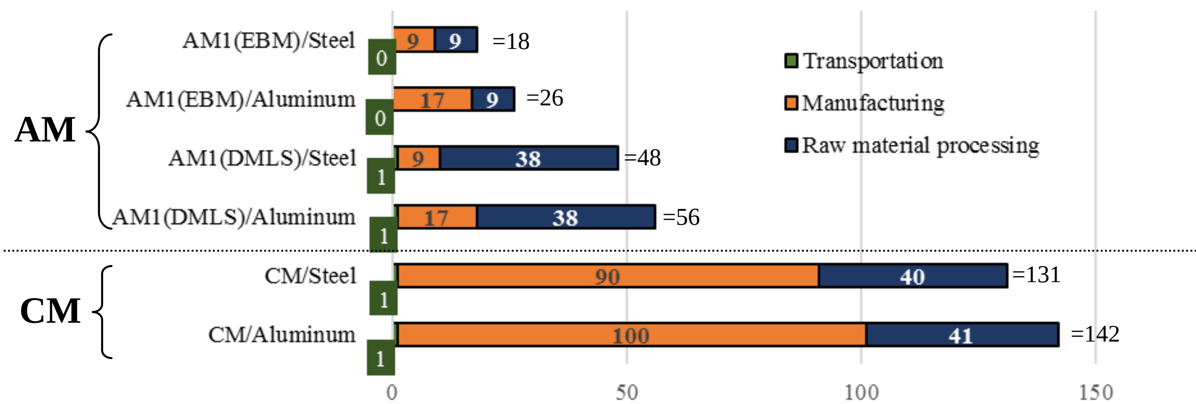

Figure 1. GHG emissions (in kg CO_2e) of CM vs. AM (DMLS and EBM technologies analyzed) per one bracket.

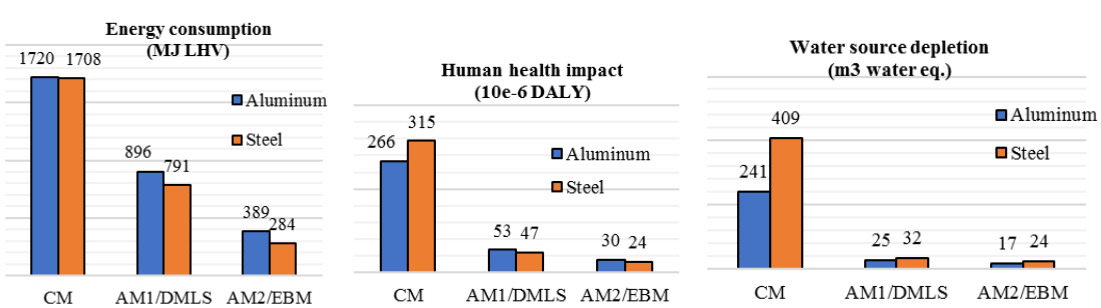

Figure 2. Environmental impacts (energy consumption, human health impact and water source depletion) of CM vs. AM (DMLS and EBM) per one bracket.

The results of the frame LCA (Figure 3) demonstrate that the environmental impacts do not vary greatly between AM and CM. The main reason was the identical input geometry and mass of the analyzed case for both manufacturing technologies. AM consumes more energy by 6.2% MJ, has 84.5% less heat waste, 0.9% less abiotic depletion of fossil fuels, and 2.4% higher GHG emissions. Analyzed AM of the frame is significantly more expensive and time consuming in comparison with CM, and it would be infeasible to use AM for the identical frame's mass and geometry. The environmental impacts of CM could be potentially reduced by decreasing aluminum extrusion waste (focus on improving the precision and accuracy of the extruded aluminum dimensions to minimize post-processing, e.g., milling). The environmental impacts and the cost of AM could be potentially reduced if using larger aluminum wire sizes without compromising the frame geometry, or reducing the mass of the frame by optimization.

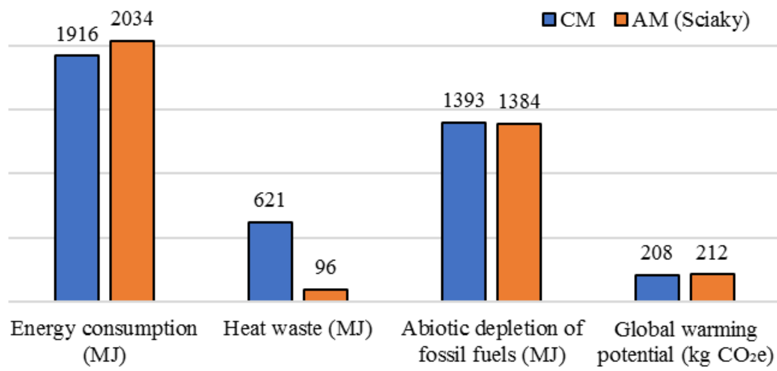

Figure 3. Environmental impacts of CM vs. AM of the curtain wall frame.

3 FUTURE WORK

The described case studies revealed that AEC practitioners lack a systematic way to rapidly and consistently assess the applicability (A), schedule (S), environmental impacts (E), and cost (C) of AM compared with CM to produce building components. If AEC practitioners had consistent transparent metrics delivered in a timely manner, they could make more informed decisions about what manufacturing methods to choose (Mrazovic 2015a, Mrazovic 2015b).

Each criterion of the ASEC assessment addresses different aspects evaluated by practitioners in the decision-making process. The applicability (A) category assesses appropriateness of an AM machine for a specific building component based on the building component requirements, like material type, geometrical constraints, and number of components. The schedule assessment (S) provides information about the time to manufacture and how this process duration could affect the scheduling on an AEC project. The environmental impacts (E) analysis compares GHG emissions, energy consumptions, human health impacts, and water use throughout the whole life cycle of an AM building component with respect to a CM counterpart. The cost assessment (C) compares AM with CM cradle to gate[1] costs of a specific building component.

During the case studies Mrazovic tracked the encountered challenges; the duration of each step and potential problems that could lead to inconsistencies in the assessment process if repeated without formalization. The future work includes formalization of the ASEC assessment

[1] A *cradle to gate* system boundary includes stages from raw material extraction to the transportation of the material or product to its site of use.

framework based on the lessons learned from the case studies, and impact assessment of the formalized assessment process on the effort and the consistency of the assessment between different assessors.

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