Environmental and Economic Implications of Distributed Additive Manufacturing

The Case of Injection Mold Tooling

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Summary

Additive manufacturing (AM) holds great potentials in enabling superior engineering functionality, streamlining supply chains, and reducing life cycle impacts compared to conventional manufacturing (CM). This study estimates the net changes in supply-chain lead time, life cycle primary energy consumption, greenhouse gas (GHG) emissions, and life cycle costs (LCC) associated with AM technologies for the case of injection molding, to shed light on the environmental and economic advantages of a shift from international or onshore CM to AM in the United States. A systems modeling framework is developed, with integrations of lead-time analysis, life cycle inventory analysis, LCC model, and scenarios considering design differences, supply-chain options, productions, maintenance, and AM technological developments. AM yields a reduction potential of 3% to 5% primary energy, 4% to 7% GHG emissions, 12% to 60% lead time, and 15% to 35% cost over 1 million cycles of the injection molding production depending on the AM technology advancement in future. The economic advantages indicate the significant role of AM technology in raising global manufacturing competitiveness of local producers, while the relatively small environmental benefits highlight the necessity of considering trade-offs and balance techniques between environmental and economic performances when AM is adopted in the tooling industry. The results also help pinpoint the technological innovations in AM that could lead to broader benefits in future.

Introduction

In recent decades, globalization and technology development have reshaped manufacturing supply chains (Mourtzis and Doukas 2013). Global manufacturers are continuously challenged by the increasing complexity of the manufacturing process, dynamic local economies, and rapidly changing demands in the world-wide market (Davis et al. 2012; Chituc and Restivo...
In this study, we quantify the life cycle energy, greenhouse gas (GHG) emissions savings potential, and the economic and lead-time impact of AM technologies for the tooling of injection molding in the United States (EOS 2013). AM can help resolve the manufacturing difficulties and enable novel designs that benefit both performance and the environment (EOS 2012b). One such innovation is the conformal cooling channels in the injection mold. Literature shows at least 10% cycle time saving from applying conformal cooling with limited engineering effort, and a range between roughly 15% and 60% of cycle time improvement for different studies (Groover 2007; Cottellee et al. 2014; EOS 2013; Huang et al. 2013; Fuges 2012; Hsu et al. 2013; Guilong et al. 2010; Hall and Krystofik 2015; Hickman and Helper 2015). In some cases, AM injection molds have led to a 75% to 125% increase in productivity and a 44°C rise in the required cooling water temperature, which results in operation profits and reduced energy consumption (EOS 2012a, 2012b). The optimized designs achieved by AM also lead to significant energy savings in other industries. For example, an accumulative energy savings of 1.2 to 2.8 billion GJ by 2050 has been identified from lightweight AM aircraft components in the U.S. fleet (Huang et al. 2015). Similar environmental and economic benefits, led by the improved performance of AM applications, were also identified in the automotive and medical industries (Reeves 2008; Direct Manufacturing Research Center 2013).

Further, distributed AM may greatly reduce the management efforts in the complex global supply chain of the injection-molding industry. In 2010, the global market for injection-molded plastics was nearly 80,000 kilotonnes (kt); the market is expected to reach 116,000 kt by the end of 2018, with a 4.9% compound annual growth rate (Grand View Research 2014). In the United States, the market size of the injection-molding industry was more than US$60 billion, which contributed about 25% of the global market (IBISWorld 2015). On the contrary, from 1998 to 2010, the U.S. tool and die industry decreased about 30% (Canis 2012), and many plastic manufacturers sourced their mold and tooling requirements from less-expensive foreign locations (US ITC 2002). The trade-offs of the cost advantage include longer lead times, increased risk of disruption due to unpredictable accidents, and quality-control challenges (US ITC 2002). With AM technology, molds may be manufactured in-house, which greatly streamlines the supply chain. Also, the process intensification and high automation brought by AM holds the promise of simultaneously preserving the cost of outsourcing, which improves the competitiveness of local manufacturers.

Despite the increasing applications, AM technology has limitations and continues to be under development. The throughput is presently low, especially for metallic AM processes, which limits AM’s applications in high-volume productions or large parts (Wöhlers 2013). Other issues, such as repeatability, roughness, and residual stresses, require additional postprocessing procedures for AM components (Huang et al. 2013; Horn and Harrysson 2012; Frazier 2014). These barriers, however, are likely to be overcome in the next 5 to 20 years because of continued research devoted to improving AM processes in industry and the scientific community (Gaausemeier et al. 2014). The implications of a mature AM technology in industries like injection molding may differ substantially compared to the technology to date.

Few studies have attempted to quantify the life cycle environmental and economic implications of AM parts and supply chains. Most studies have focused on the direct electricity demand of different AM processes without considering life cycle impacts and comparison to the energy requirements of the CM processes that are replaced (Baumers et al. 2010; Luo et al. 1999; Mognol et al. 2006; Sreenivasan and Bourrell 2009; Kellens et al. 2010). Some studies have investigated the life cycle environmental or economic impacts of AM components, but few have integrated these analyses (Morrow et al. 2007; Telenko and Carolyn Conner 2012; Kreiger and Pearce 2012; Huang et al. 2015; Khajavi et al. 2014), which preclude a comprehensive understanding of the environmental and economic trade-offs of AM technology. Moreover, these studies rarely consider the technological development of AM (Khajivi et al. 2014), which may limit their findings of the impact of AM on existing cases rather than future industries. In addition, none of the studies has considered temporal implications (e.g., lead-time and downtime changes) because of the distinctive characteristics of the AM supply chain and, by extension, the environmental and economic implications of the temporal differences.

The present study addresses this quantitative knowledge gap for the case of injection mold tooling in the United States. The tooling of injection molding was chosen for this analysis on the basis of a thorough case study that includes data to facilitate such an analysis, but the modeling methodology and findings applied in the analysis are broadly applicable to other AM components. The analysis considers the uncertainty of the performance in current and future advanced AM
technologies for direct manufacturing and remanufacturing of an injection mold and compares the lead time, life cycle energy, GHG emissions, and cost compared to the case of CM on- and offshore in an analytically consistent manner. Variables related to locations, policies, technologies, productions, and supply chains are also considered. Such analyses are important for understanding the entire picture of AM’s role in reducing industrial energy use and GHG emissions while raising global competitiveness. Furthermore, it helps pinpoint the technological innovations that can lead to broader benefits in the future.

Methodology

The analysis framework used in this case study consists of four major steps. First, we selected a basic design of the mold and determined basic parameters for manufacturing the mold and injection molding on the basis of four scenarios depending on the manufacturing processes (CM/AM), manufacturing locations (onshore CM/offshore CM), and technology performances (current AM/future AM with projected advanced performances). Second, we developed a lead-time analysis model to estimate the lead-time variances of different supply chains of AM and CM for the four scenarios. Third, we developed a production and maintenance scheduling model to estimate the potential downtime implications of the AM mold with current and future performances over traditional molds. Fourth, we developed a cradle-to-grave manufacturing life cycle inventory (LCI) and life cycle economic model to estimate the energy, GHG emissions, and cost-saving potential associated with AM under current and projected performances. We selected a functional unit of 1 million cycles of injection molding production of a 137-gram (g), 160-millimeter diameter plastic product with the mold, which is the designed lifetime of the mold (Johnson 2009; Gantar et al. 2013). Together, these steps facilitated an integrated analysis of net changes in lead time, downtime, primary energy use, GHG emissions, and production economy of a representative case of U.S. injection molding attributable to the distributed AM mold with present technology or future projected technology or compared to a traditional CM case. Each step is summarized in the sections Cases and Scenarios, Lead-Time Analysis, Production and Mold Maintenance Scheduling Analysis, and Life Cycle Energy, Emission, and Economic Analysis. Further details about the approaches, data sources, calculations, and models of each step are provided in the Supporting Information available on the Journal’s website.

Cases and Scenarios

We considered a one-cavity mold and plastic product design developed by Gantar and colleagues (2013), which identified the energy consumption, cost, and operation parameters related to the mold design, manufacturing processes, and injection molding. The mold primarily consists of two categories of components. The first group includes mold cavities and mold cores (known as tool inserts), which directly determine the geometry of the injection-molded parts. The rest are mold bases, where the mold cores and cavities are mounted to fixed plates, moving plates. The bases also include sprue bushing, ejector bar, and others. In this study, we developed four design cases for different manufacturing pathways based on the associated parameters of the original mold design: (1) basic design; (2) design avoiding the use of the beryllium-copper (BeCu) alloy; (3) innovative design for the AM process with conservative improvement; and (4) innovative design for the AM process with aggressive improvement. In the first case, we applied all parameters in the original mold designs. In the second case, we slightly altered the basic design parameters to avoid the use of BeCu alloys, which is specifically applied to U.S. mold manufacturers because of the stricter U.S. standards in exposure limits of beryllium (OSHA 2015; Morrison 2015). The third case represented the innovative design of mold cores and cavities achieved by AM with conservative improvement in performances, including less cooling time and cycle time. We assumed that the other components were the same as used in the original design. Because AM is a rapidly changing technology, the fourth case represented an aggressive mold core and cavity design that may be achieved by using an advanced AM technology near maturity. Further improvements in mass reduction, increased cooling efficiency, and shorter cycle time is assumed based on the existing case studies in the literature (Fuges 2012; Hsu et al. 2013; Guilong et al. 2010; Hall and Krystofik 2015). Details of the estimations and assumptions can be found in section 1 of the supporting information on the Web.

In this study, we assumed three cases of manufacturing pathways, including a CM process case, AM processes with a current technology performance case, and relative advanced AM processes with a projected performance case. We assumed direct metal laser sintering (DMLS) as the major AM platform for producing the mold cores and cavities (EOS 2013). Since CM has been mature for many years and AM technology is still under development, we assumed a case of AM processes with advanced AM technologies with necessary performance improvement projected in different innovation roadmap studies to compare the impact of manufacturing with the following technological development: higher machine utilization rate; lower machine cost; lower material cost; higher machine throughput; increased automation; and increased machine efficiency (Gausemeier et al. 2014). The improvement projections in the roadmap studies were developed based on technology assessments, case studies, and technical surveys of AM experts in academia, business, and governmental agencies.

These technological developments can be achieved through enhanced process controls, improved software, and professionals with a deeper understanding of the process. In fact, new AM technologies under development display potentials in reaching the assumed technical targets; for example, Toshiba claimed a new laser metal deposition system with 10 times faster than the current process led by innovative nozzles to be introduced.
in 2017 (Toshiba Press Releases 2015). The latest AM system (SLM 500HL) of SLM Solutions has already offered a build rate of up to 105 cubic centimeters per hour (cm³/h) with 90% improvement led by quad-laser technology (SLM Solution 2016). Currently, the cost of materials for AM is one barrier to technology adoption in the industries. Researchers have identified that the costs are much higher than the estimated real cost and predicted it to drop because the major raw material suppliers have not entered this market because it is still marginal (Roland Berger Strategy Consultants 2013). Machine throughput and vacancies have a similar influence on the unit cost of AM; however, optimizations of AM capacity to the demand can be achieved much more easily compared to innovations in increasing the machine capabilities.

In addition, we considered three supply-chain cases to cover the potential options in ordering the mold. The first case considered an international supply chain in which the mold was designed and manufactured in China. The second case considered the onshore supply chain of the mold in which the mold was designed and manufactured in the United States. By printing out the digital design directly instead of going through many processing steps with different machines, AM could potentially reduce the difficulties and barriers in manufacturing the final parts, which helps to achieve a “distributed” manufacturing supply chain in the future. The last supply-chain case assumed that the mold was manufactured in-house by the injection-molding manufacturer itself with AM.

To analyze different characteristics and the associated impact of distributed AM over CM in mold fabrication, four scenarios were generated by combinations of the cases of design, manufacturing pathways, and supply chains: (1) off-shore CM; (2) onshore CM; (3) in-house AM assuming current performance; and (4) in-house AM assuming mature performance. These four scenarios included all major potential options in mold manufacturing for comparison of distributed AM over CM, including representative international or U.S. supply chains, CM and AM pathways, current AM technologies, and potential improvements and their associated differences. Table 1 summarizes our estimates and assumptions for the related information of manufacturing process and supply chains in the four scenarios. Figure 1 shows the manufacturing processes of four scenarios.

**Lead-Time Analysis**

For the mold made through different AM and CM supply chains in scenarios 1 to 4, the next step was modeling the lead time of the mold in each scenario and calculating the differences potentially introduced by distributed AM. As shown in figure 1, the lead time for manufacturing the mold includes time spent in designing, process planning, AM or CM, finishing, testing, and transportation (Bryce 1996; Gantar et al. 2013; Gunasekaran et al. 2001). The lead time is an important index for manufacturing, and having detail estimation in time can help better estimate the time-dependent impact such as energy use in machines and labor cost (Emmett and Granville 2007). We derived the lead-time data for each step by estimating the time spent in manufacturing and finishing using the original time estimation from Gantar and colleagues for CM, and time estimation models constructed for AM based on the machine throughput and the mass of the mold (Gantar et al. 2013; Gausemeier et al. 2014; EOS 2015; 3T RPD 2015). The times needed for designing, process planning, and testing were determined by applying the average lead-time structure of local manufacturers in each scenario based on the manufacturers’ surveys on lead time (Fallböhmer et al. 1996). The transportation time was estimated by using literature data and online commercial calculators (Grönkvist 2015; The World Bank 2014; US DOT 2012; SeaRates 2014). Further details on all data sources and assumptions are provided in section 2 of the supporting information on the Web.

**Production and Mold Maintenance Scheduling Analysis**

We further analyzed the temporal differences in production and maintenance scheduling of a distributed AM mold over a CM mold after it is ready for injection molding. A mold for large-volume production usually requires regular preventive maintenance (PM) to ensure the mold’s performance and product quality (Ullmer 2014; Groover 2007), which adds hours to days of downtime (MoldMaking Technology 2013). We considered the following maintenance processes (see figure 1):

- **Partial line (P/L) PM**: Dry ice blasting cleaning occurs while the mold is still fully assembled and mounted in the injection-molding machine (MoldMaking Technology 2013; Johnson 2004);
- **Partial line PM with inserts and cavity cleaning (partial disassembly or P/D)**: All producers are the same as with P/L, except that this option requires partial disassembly of the inserts and cavity for detail cleaning (MoldMaking Technology 2013);
- **Full PM**: The mold is taken out of the press and sent to a PM shop, where parts are ultrasonic cleaned and maintained in detail (MoldMaking Technology 2013; Johnson 2007b); and
- **Full PM with repairs**: This option is the same as the full PM. In addition, the tool inserts are repaired (MoldMaking Technology 2013; Johnson 2007b). We assumed that plasma-transfered arc (PTA) welding and direct energy deposition (DED) were the repairing process for the CM and AM processes with 1% mass of the tool inserts being repaired (Wilson et al. 2014; Metal Additive Manufacturing 2015; Bryce 1996).

Different preventive maintenance processes were assumed to perform routinely and the processes and the maintenance interval for different scenarios were assigned based on the mold design and existing literature. The downtime estimates for maintenance processes were either compiled directly from published values in the literature or calculated with a time estimation model specifically constructed for the processes (MoldMaking
Table 1  Mold designs for different scenarios

| Item                        | Scenario 1                        | Scenario 2                        | Scenario 3                           | Scenario 4                           |
|-----------------------------|-----------------------------------|-----------------------------------|--------------------------------------|--------------------------------------|
|                             | Designed and manufactured in China with CM | Designed and manufactured in the United States with CM | Designed and manufactured in-house with AM assuming current performances | Designed and manufactured in-house with mature AM assuming advanced performances |
| Mold                        |                                   |                                   |                                      |                                      |
| Total, $M_{\text{output}}$ [kg] | 323                               | 340                               | 320                                  | 315                                  |
| Plate [kg]                  | 235                               | 235                               | 235                                  | 235                                  |
| Tool insert, $M_{\text{output}}$ [kg] | 30                              | 45                                | 30                                   | 25                                   |
| Others (pin and other systems) [kg] | 58                              | 60                                | 55                                   | 55                                   |
| Materials input for mold    |                                   |                                   |                                      |                                      |
| Tool steel, $M_{\text{input}}$ [kg] | 99                               | 124                               | N/A                                  | N/A                                  |
| Maraging steel 1.2709, $M_{\text{input}}$ [kg] | N/A                             | N/A                               | 92.4                                 | 88                                   |
| Steel plate, $M_{\text{input}}$ [kg] | 235                             | 235                               | 235                                  | 235                                  |
| BeCu, $M_{\text{input}}$ [kg] | 3                                 | N/A                               | N/A                                  | N/A                                  |
| Aluminum, $M_{\text{input}}$ [kg] | 0.46                            | 0.46                              | 0.46                                 | 0.46                                 |
| Stainless steel, $M_{\text{input}}$ [kg] | 1                               | 0.75                              | 0.75                                 | 0.75                                 |
| Materials input for inventory tool insert |                                   |                                   |                                      |                                      |
| Tool steel, $M_{\text{input}}$ [kg] | 33.75                           | 56.25                             | N/A                                  | N/A                                  |
| BeCu, $M_{\text{input}}$ [kg] | 3.75                             | N/A                               | N/A                                  | N/A                                  |
| Mold production             |                                   |                                   |                                      |                                      |
| Manufacturing technology    | CM                                | CM                                | DMLS (current performance)           | DMLS (improved performance)          |
| AM machine throughput (cm³/h) | N/A                             | N/A                               | 15                                   | 100                                  |
| Cutting tools consumed, $M_{\text{input}}$ [kg] | 3                              | 3                                 | 1                                    | 1                                    |
| Injection molding           |                                   |                                   |                                      |                                      |
| lifetime, $L$ [cycles]      | 1 million                         | 1 million                         | 1 million                            | 1 million                            |
| Cooling time, $T_{\text{cooling}}$ [s/cycle] | 39                            | 37                                | 23.4                                 | 11.7                                 |
| Cycle time, $t_c$ [s/cycle] | 58                               | 56                                | 42.4                                 | 30.7                                 |
| Clamping force [10³ kg]     | 90                               | 90                                | 90                                   | 90                                   |
| Plastic material (PP 40% GF) Consumption, $m_{\text{input}}$ [g/part] | 137.4                         | 137.6                             | 137.0                                | 137.0                                |
| Expected reject rate, $\gamma$ [%] | 0.5                           | 0.4                               | 0.4                                  | 0.2                                  |
| Energy consumption for injection molding, $e_5$ [kWh/part] | 0.138                         | 0.136                             | 0.110                                | 0.090                                |

(Continued)
Table 1  Continued

| Item | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 |
|------|------------|------------|------------|------------|
|      | Designed and manufactured in China with CM | Designed and manufactured in the United States with CM | Designed and manufactured in-house with AM assuming current performances | Designed and manufactured in-house with mature AM assuming advanced performances |

| Transportation | mode | Diesel truck/freight cargo ship/diesel truck | Diesel truck | N/A | N/A |
|----------------|------|--------------------------------------------|--------------|-----|-----|
| Distance, \(d\) | 500 km/13,000 km/500 km | 500 km | N/A | N/A |

- Estimated based on the plastic product design.
- Not applicable.
- Estimated based on the scrap rate calculated from the manufacturing data of the basic design.

kg = kilograms; BeCu = beryllium copper; \(cm^3/h\) = cubic centimeters per hour; \(s/cycle\) = seconds per cycle; PP = polypropylene; GF = glass fiber; g/part = grams per part; kWh/part = kilowatt-hours per part; CM = conventional manufacturing; N/A = not applicable; km = kilometers; AM = additive manufacturing; DMLS = direct metal laser sintering.

Figure 1  System boundaries for the life cycle of injection molding in different scenarios. AM = additive manufacturing; BeCu = beryllium copper; CM = conventional manufacturing; DED = directed energy deposition; DMLS = direct metal laser sintering; EDM = electrical discharge machining; GF = glass fiber; P/D = partial disassembly; P/L = partial line; PM = preventive maintenance; PP = polypropylene; PTA = plasma-transferred arc.

Life Cycle Energy, Emission, and Economic Analysis

To estimate net changes in life cycle energy use, GHG emissions associated with a shift from offshore CM to distributed AM (as summarized in table 1), we developed a process-based LCI model of the injection molding life cycle systems depicted...
in figure 1. The functional unit is 1 million cycles of the injection molding (Gantar et al. 2013), which is the designed lifetime of the mold in all four design cases. The system boundary includes the following major process steps for CM and AM pathways in the four scenarios: material production; mold manufacturing; mold transportation; mold use, including plastic part production, mold maintenance, and repair; and the end of life (EoL) of the mold. Each process step was modeled on the basis of primary energy use and GHG emissions data for the depicted unit processes obtained from the literature. Material production processes included production of ingot, plate, and powders from primary and secondary metal production processes (Morrow et al. 2007; NREL 2012; ANL 2012; Ashby 2012; Norgate et al. 2007; Kruzhnov and Arnhold 2012; Nuss and Eckelman 2014; Allwood et al. 2011; Benes 2008). For the EoL of the mold, open-loop recycling of the materials was also considered, since the mold is made in metals, and open-loop recycling is widely applied for metals (Bergsma and Sevenster 2013). Molding manufacturing included machining, finishing, electrical discharge machining (EDM), polishing, and DMLS (for AM) (Gantar et al. 2013; Kara and Li 2011; Dahmus and Gutowski 2004; Advanced Metal Improvement Technologies 2014; Kong et al. 2013; Peças and Henriques 2009; Gausemeier et al. 2014). Mold transportation included shipment by diesel trucks and cargo ships (NREL 2012). Plastic part production included the polypropylene (PP) 40% glass fiber (GF) plastic material production, conveying the material, and the process of injection molding (Ashby 2012; Thiriez 2006; GlassFiber Europe 2012; Lei et al. 2010; Gantar et al. 2013). Mold maintenance and repair included material production of dry ice and steel powders, dry ice blasting, ultrasonic cleaning, PTA welding for CM repairing, DED for AM repairing, and finishing (MoldMaking Technology 2013; Masta et al. 2014; Johnson 2007b). Primary energy and GHG emissions intensities of all processes, including the corresponding data sources and analysis assumptions, are summarized in sections 4.1 to 4.4 of the supporting information on the Web. The mean values of energy and GHG emission intensity collected from the literature are applied in the estimations.

The governing equation for the life cycle primary energy associated with the mold is as follows:

\[ E_i = \sum_k E_k = \sum_r e_{1r} \cdot M_{inputr} + \sum_q e_{2q} \cdot T_{q} + e_{3} \cdot M_{output}, \]

\[ + L \cdot (e_{4} \cdot m_{input} + e_{5}) + \sum_j n_j \cdot e_{6j}, \]

where for scenario \( i \), \( E \) is the primary energy use (megajoules [MJ] per 1 million cycles), \( e \) represents the primary energy intensity of a process step (MJ/kg [kilogram] or MJ/hour or MJ per cycle), \( M \) represents the mass into or out of a process step for manufacturing the mold (kg), \( T \) is the manufacturing time for a process step, \( L \) is the mold lifetime (cycle), \( m \) is the mass input and output in injection molding (kg), \( n \) represents the number of times maintenance option \( j \) is performed, and \( k \) represents the life cycle stage. The governing equation for the life cycle carbon dioxide equivalent (CO\(_2\)-eq) emissions associated with

\[ C_i = \sum_k C_k = \sum_r e_{1r} \cdot M_{inputr} + \sum_q e_{2q} \cdot T_{q} + e_{3} \cdot M_{output}, \]

\[ + L \cdot (e_{4} \cdot m_{input} + e_{5}) + \sum_j n_j \cdot e_{6j}, \]

where \( e \) represents the CO\(_2\)-eq emissions intensity of a process step (kg CO\(_2\)-eq/kg, or kg CO\(_2\)-eq/hour or kg CO\(_2\)-eq per cycle), and \( C \) represents the CO\(_2\)-eq emissions associated with a process step (kg CO\(_2\)-eq per 1 million cycles).

We also developed a life cycle cost (LCC) model of the injection-molding life cycle systems depicted in figure 1. Four cost components were considered in the LCC model for each process: material cost; machine cost; labor cost; and energy cost. Besides the processes, the LCC model also included designing, process planning, assembling, and testing in molding manufacturing, as well as inspection, diagnosis, disassembly, and assembly in mold maintenance and repair. The unit cost of all processes, including the corresponding data sources and analysis assumptions, are summarized in sections 4.1 to 4.4 of the supporting information on the Web.

The governing equation for the LCC associated with the mold is as follows:

\[ S_i = \sum_k S_k = \sum_r c_{1r} \cdot M_{inputr} + \sum_q ((c_{2,MFGq} + c_{2,Labour}) \cdot \cdot \cdot T_{q} + c_{2,energy} \cdot E_{2q} + S_j) + L \cdot (c_{4} \cdot m_{input} + \cdot \cdot \cdot (c_{5,MFG} + c_{5,Labour}) \cdot T_{i} + c_{5,energy} \cdot e_{5}) + \sum_j n_j \cdot \cdot \cdot (c_{6,MFG} + c_{6,Labour}) \cdot T_{i} + c_{6,energy} \cdot e_{6j}), \]

where \( c \) represents the unit cost (US$ per kg, US$ per hour, or US$ per MJ) of material, unit process, labor, and energy, and \( L \) represents the mold lifetime. Here, MFG, labor, and energy represent the machine, labor, and energy cost, respectively, and the definition of \( i \) and \( j \) is the same as the equations for energy and emissions. The value of \( S \) represents the cost associated with manufacturing the mold or injection molding (US$ per 1 million cycles).

**Results and Discussion**

Figure 2 highlights the lead-time and cradle-to-gate impact of the mold, while figure 3 shows the comparison of payback time and the life cycle impact allocated to the unit injected product among all four scenarios. As estimated in the study, ordering a mold required about 9 weeks from the U.S. supplier or 11 weeks from the offshore supplier. Without transportation, which is estimated to be about 4 weeks, the mold is estimated to take 6.7 weeks to prepare in China, which is about 22% faster compared to the U.S. mold. These lead-time estimates for CM correlate with the findings in the literature, manufacturer surveys, and government reports (US ITC 2002).
The AM supply chains presently show a considerable 12% lower lead time for the mold credited to on-site manufacturing compared to the long supply chains in offshore CM pathways. Compared to onshore CM, the current AM lead time is 4 days slower. In the AM supply chains, as much as 56% of the time is spent in manufacturing the component and finishing it, which is more than 60% longer compared to CM and chips away the time saved attributable to streamlining the supply chain by eliminating the transportation. Because the manufacturing time makes up a large portion of fabrication, the potential development in the AM machine throughput in the future plays the most significant role in improving the lead time. A metallic AM process with building rate at the magnitude of 100 cm$^3$/h in the future is estimated to have a lead time of only 4.3 weeks, which greatly saves waiting in the injection-molding plant, compared to 10.6 weeks for offshore CM pathways or 8.8 weeks from the U.S. suppliers.

The embodied primary energy and emissions of the CM mold set are about 32 GJ and 2.7 tonnes (t) of CO$_2$-eq, respectively, if the mold is conventionally manufactured overseas. The U.S. mold consumed barely 1 GJ more, but generated 11% less GHG emissions due to the cleaner electricity grid. About 10% to 12% of the energy consumption can be traced back to manufacturing and transport of the inventory tool inserts for CM pathways, which could potentially be saved by eliminating inventory tools because of shorter downtime of AM mold. The energy-intensive AM processes to build such a mold required 27 GJ of primary energy, which led to 25% greater embodied primary energy use of the mold compared to CM pathways. However, the technology holds the potential to reduce 32% of the process energy use if the AM technology is improved in machine and material efficiency, which reverses the larger energy use to 2 to 3 GJ of upstream savings from the AM replacing CM pathways. The energy consumption for maintaining and repairing the mold during 1-million-cycle productions can be as large as 50% to 55% of the embodied energy use for the CM molds, for which the maintenance impact during the use phase is also included (dotted lines) for better comparison in figure 2. Using the AM mold led to more than a 65% energy reduction in maintenance due to the longer maintenance interval required when the mold was operated in optimized cooling-effective conditions provided by the conformal cooling achieved by AM. This energy savings potential can reach to 83% with better engineering optimal design.

The mold set for sustaining a 1-million-cycle production consumes about 10.1 terajoules for CM scenarios, in which the plastic material production and injection molding in the use phase dominate and contribute 99% of total impacts combined. Allocated to each plastic part produced, the embodied energy consumption and emission is about 10.2 MJ and 0.48 kg CO$_2$-eq per part. The AM mold with novel designs led to about 310
to 530 GJ of primary energy savings and 20 to 35 t CO$_2$-eq emissions savings, primarily due to improved cooling efficiency in the injection-molding cycles, which equals 3% to 5% and 4% to 7% of the life cycle energy use and emissions, respectively, depending on the AM technology performances. These savings help reduce about 0.2 to 0.5 MJ of embodied energy and 0.2 to 0.4 kg of emission for every plastic part produced with the additive manufactured mold.

The upfront cost of the mold was estimated as US$18,760, if the mold is outsourced to China with the CM pathway as displayed in figure 2. The U.S. mold cost 70% more because of the much higher labor cost for designing and manufacturing.
Currently, the cost of such a mold made by AM can be as much as US$51,000, with about tenfold material cost and high manufacturing cost, which slows AM’s adoption by manufacturers. Such high costs are due to pricey AM raw materials and machines, low utilization rate, and machine throughput. Improvements in these areas could greatly reduce the cost and have the potential in competing in price (i.e., about US$4,000 margin compared with current molds) with outsourcing CM, which greatly increases the local manufacturers’ attractiveness in global competition.

The unit cost of injection molding the plastic part associated with CM mold considering the full life cycle is about US$0.56 per part. The major costs are for plastic material and injection molding and consist of more than 90% of the total LCC. Majorly led by the improved productivity associated with the AM mold, the unit cost for each part injection molded is reduced by 13% or US$0.8/part. The improved design with conformal cooling could potentially lead to a 35% unit cost reduction for this case if technology allows. If we are assuming the sale price of the plastic injection-molded product as US$0.8 (Dow Chemical 2014), the payback time for the AM mold is about 135 days, which is still competitive compared to 115 days for offshore CM and 147 days for onshore CM, although the upfront cost of the AM mold is substantially higher. If the AM technology develops to a matured level as discussed in different roadmap studies, the improvements combined could potentially lead to 43 days of payback time, which is barely 10 days of production after the injection mold reaches the injection-molding plant.

Figure 4 highlights the influential variables in the AM scenario and their impact on the life cycle energy consumption and life cycle cost for this case under uncertainties and assumptions. The mass of the tool produced by AM, the AM process energy intensity, and the process scrap rate are the dominant factors to the cradle-to-gate energy consumptions, while the plastic material used per production cycle, cooling time reduction, and reject rate in production influence the full life cycle energy consumption allocated to each injection-molded plastic part. The upfront cost is sensitive to the machine throughput, lifetime, utilization rate, and price of AM technologies and the AM

Figure 5 Roadmap showing potential impact in GHG emissions and costs for deploying distributed additive manufacturing (AM) with technological development. CM = conventional manufacturing; CO$_2$ = carbon dioxide; GHG = greenhouse gas.
Conclusion

In this study, we presented an integrated technoeconomic model to estimate lead time, life cycle primary energy use, GHG emissions, and costs of a typical injection mold for comparison of distributed AM over CM in scenarios considering different supply chains and future technological developments. Results from the analyses in this study yielded potential savings of 12% to 60% lead time, 70% to 80% downtime, 3% to 5% primary energy, 4% to 7% GHG emissions, and 15% to 35% cost for distributed AM over CM through the 1 million injection molding cycles. Realizing optimized designs, improved machine throughput, reducing machine vacancy, and reduced material cost are identified as the AM technological developments that lead to most potential benefits in future.

The environmental benefit of AM in this tooling case is relatively marginal compared to the economic advantages, which indicates the importance of balancing the environmental-economic trade-offs with necessary measures such as developing tool designs with optimal scrap rate. The environmental benefit percentage may be further reduced for other tooling cases with different parameters, such as multiple-cavity tools. The scope of this study does not consider the possible additional energy, emissions, and cost implications from warehousing the materials, inventory tools, and batches of products before they were distributed to customers. Also, since the scrap rate of manufacturing the mold with CM and the importance of lightweight materials may not be as high as other components such as those in the aircraft industry, the material efficiency advantages of AM were not well displayed and discussed in this study. Those savings potentials, especially environmental benefits, for distributed AM could be much larger if industries with high priorities in reducing mass and scrap rate were involved.

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Supporting Information

Supporting information is linked to this article on the JIE website:

Supporting Information S1: This supporting information includes a table summarizing the related information of the mold design and the plastic part produced from the mold, a table summarizing estimates and assumptions for the related information of the mold design, manufacturing process, and supply chains for four different production scenarios, information on lead-time analysis, information on injection molding and mold maintenance scheduling analysis, and information on life cycle inventory and life cycle cost.