Journal of Cleaner Production, Volume 107, November 2015, pp. 615-625
DOI:10.1016/j.jclepro.2015.05.009

Direct Digital Manufacturing: Definition, Evolution, and Sustainability Implications

Danfang Chen, Steffen Heyer, Suphunnika Ibbotson, Konstantinos Salonitis, Jón Garðar Steingrímsson, Sebastian Thiedee

Highlights

- An overview of direct digital manufacturing is presented from different perspectives.
- Direct digital manufacturing paradigm as an evolution of traditional manufacturing.
- Direct digital manufacturing discussed and analysed under sustainability prism.
- Energy consumption comparison for manufacturing using SLS and injection moulding.

Abstract

One of the hot topics currently in manufacturing domain is direct digital manufacturing. With introduction of cheap three-dimensional printers, the direct digital manufacturing seems to become a new manufacturing paradigm with an entirely different impact on society; nevertheless how this will impact the society and the differences between the paradigms are unclear. According to this background, this paper presents a comprehensive analysis of direct digital manufacturing from different perspectives in comparison to various traditional manufacturing paradigms. Authors are using a societal viewpoint to see, describe and analyse the subject instead of traditional manufacturing viewpoint. For the better understanding of direct digital manufacturing origins, a classification and historical background about available techniques are described.

Furthermore, direct digital manufacturing as a paradigm is analysed and compared with craft production, mass production and mass customisation. Direct digital manufacturing's sustainability aspects related to social, economical and environmental dimensions are gathered and analysed for a better insight of this technique. A detailed case study demonstrates the energy use differences of direct digital manufacturing and mass production in depth. According to the present work, direct digital manufacturing has the possibility of combining the advantages of the other production paradigms and can have a positive impact on sustainable development; yet, there are several challenges to overcome both in technical and sociality aspects. A challenge within the social aspects can be the life style changes which can impact the job market, working environment, waste management and more.

Published by Elsevier. This is the Author Accepted Manuscript issued with: Creative Commons Attribution Non-Commercial No Derivatives License (CC:BY:NC:ND 4.0).
The final published version (version of record) is available online at DOI:10.1016/j.jclepro.2015.05.009. Please refer to any applicable publisher terms of use.

Keywords

Additive Manufacturing; Direct Digital Manufacturing; Sustainability; Manufacturing Paradigm;

List of acronyms

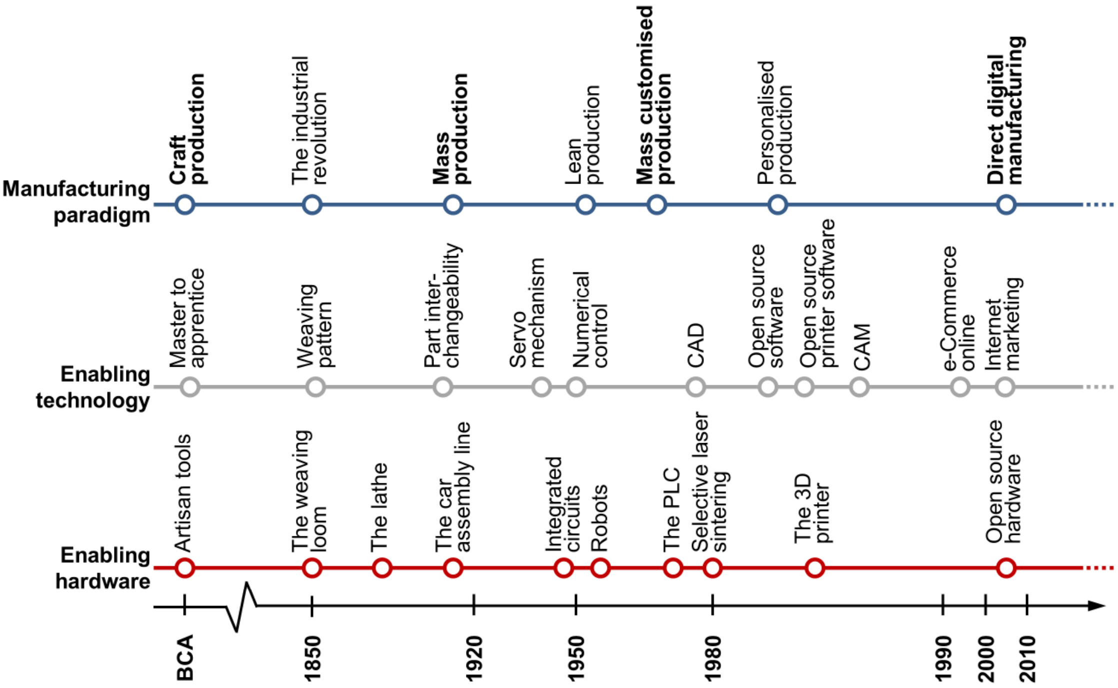
3D: Three-Dimensional
AM: Additive Manufacturing
BJ: Binder Jetting
CNC: Computer-Numerical Controlled
CIM: Computer Integrated Manufacturing
CAD: Computer-Aided Design
CAM: Computer-Aided Manufacturing
CAE: Computer-Aided Engineering
DDM: Direct Digital Manufacturing
DLP: Digital Light Processing
DMD: Direct Metal Deposition
DMLS: Direct Metal Laser Sintering
EBM: Electron Beam Melting
FDM: Fused Deposition Modelling
ICT: Information and Communication Technology
IM: Injection Moulding
KPI: Key Performance Indicators
LPF: Laser Powder Forming
LOM: Laminated Object Manufacturing
LCA: Life Cycle Analysis
PLA: Polylactic Acid
SL: Stereo-Lithography
SLS: Selective Laser Sintering
UAM: Ultrasonic Additive Manufacturing
UNCSD: United Nations Commission for Sustainable Development

1 Introduction

Starting from manual crafting with a very slow pace, humanity reached industrial revolution and mass production in the beginning of 20th century. Since then, with a constantly increasing technological development pace, manufacturing systems evolved to more lean ones which are able to produce economically smaller batch sizes. Lean manufacturing allowed the production of highly standardised products with high quality. Additionally, the batch sizes were reduced offering the premises of customisation (Womack et al., 2007). Mass customisation was initiated through fragmented demand and homogeneous niches, where consumers wanted low cost products with high quality. Industries offering mass customisation were different, such as the beverage industry, the information and communication technology, the insurance industry, the fast-food industry and the banking industry. Common practice was to offer a portfolio of product families with strong core familiarities but different varieties, an example of which would be basic cola that was sold as diet, non-diet, caffeinated and caffeine-free. A new trend is the mass personalisation. Products are produced under the framework of mass customisation and include a distinctive feature associated with the consumers such as labelling the consumers name on the products. Evidently, this trend is very close to the mass customisation but the niches are now heterogeneous; therefore, the system's flexibility has to be capable of handling this requirement (Joseph Pine, 1993).

To support this trend, additive manufacturing (AM) such as rapid prototyping and stereo-lithography plays a major role since it can reduce development time and cost in order to check the design, mainly of prototypes (Gibson et al., 2010). AM is the process of fabricating an artefact (geometrically defined product), which is directly derived from a 3D CAD model without the need for process planning in advance of manufacturing. Many technological advances of AM methods have been developed since 1980s including 3D printing. Such technology attracts many industries and individuals and subsequently leads to direct digital manufacturing (DDM). The way products are now being produced is under a redefinition through DDM. Parts will no longer be produced in a factory, assembled to final products and shipped to customers. Instead, these products are manufactured right at or close to the customer utilising additive manufacturing and directly derived from a digital model (Gibson et al., 2010). Thus, AM is evolving into DDM as an interconnection of additive manufacturing equipment, computers through a network (e.g. internet and servers) and computer software.

Error! Reference source not found. depicts a selected view of manufacturing paradigms on a time line with the comparatives of the enabling technology and the enabling hardware. Closer to the present time, the enabling technologies and the hardware become bundled as is present with the DDM.



BCA: Before common era

Figure 1: A time line of different manufacturing paradigms that compares their enabling technology and hardware (selected view)

It seems that DDM has become a production paradigm for the 20th century, due to its large potential to change today's manufacturing. Whether or not this vision is accurate, DDM in its different forms seems to have the potential that may change process chains, material efficiency in products business models and even the product-user relationship. It has the possibility of combining the advantages of the production paradigms specified here above, into personalised high quality products with the batch size of one. However, given this strong potential change in manufacturing, the question arises whether DDM also has a positive impact on the sustainability of manufacturing.

Sustainability has been a major concern in industries for many years (Duflou et al., 2012; Umeda et al., 2012). Related key performance indicators (KPI) allow manufacturers to monitor and assess all the essential perspectives which includes the economic, social and environmental dimensions (Ibbotson and Kara, 2014; Ibbotson et al., 2013). Many studies have analysed and developed tools for assessing sustainability for a manufacturing system and the entire life cycle of a product including the usage and the end-of-life stages (Manmek et al., 2010). A number of tools have been developed to support sustainable manufacturing, including green supply chains, reverse logistics, design for environment and design for disassembly (Moosavirad et al., 2013; Salonitis and Stavropoulos, 2013; Li et al., 2012; Thiede, 2012). Limited studies are found in assessing certain sustainability aspects of particular technologies of AM and DDM, (Kunnari et al., 2009; Morrow et al., 2007; Vinodh, 2010).

Therefore, this paper aims to clarify and analyse the main aspects of DDM and also its sustainability in order to provide an important foundation for manufacturers in enhancing their manufacturing systems. The next section discusses the evolution of DDM which is followed by a comparison of DDM and the traditional manufacturing paradigms. This highlights their differences on the technicality, how the roles of the end user changes - from passive consumer to active consumer - and ending at the persons involved in producing and consuming the artefacts, the “prosumer” DDM. Besides general discussions on the sustainability related aspects of DDM, specific case studies are given in a context of energy use.

2 Evolution of Direct Digital Manufacturing

As indicated before, DDM is an interconnection of (decentralised) additive manufacturing equipment and modern information and communication technology (ICT). ICT, especially the internet, allows to match consumer demands and supply capacities in real-time, only limited by physical logistic handling of artefacts. Starting with computer-numerical controlled (CNC) machine tools and evolving into computer integrated manufacturing (CIM), computer technology improved efficiency of manufacturing in many ways greatly. The main technological breakthrough of computer and information technology, allowed the development of both desktop processes and DDM in the manufacturing area. These are especially the various computer-assisted technologies such as computer-aided design (CAD) that started in a 2D drawing environment, later to be augmented with a 3D drawing environment (3D CAD), computer-aided manufacturing (CAM) and computer-aided engineering (CAE).

DDM describes the process of using a 3D (CAD) model for directly fabrication without the need for process planning (Gibson et al., 2010). DDM is nowadays not only applied to create design studies but also final products, Gibson defines it as “additive manufacturing for production or manufacturing of end-use components” (Gibson et al., 2010). In additive manufacturing, material is added layer by layer, derived as thin cross-section from the 3D model. The layer thickness determines the resolution of the manufactured product. Common materials are e.g., aluminium, steel alloys, precious metals, plastics used in a powder form and paper; but wood, wax, paper, clay, concrete, sugar and chocolate are possible to be used as filament. Material combinations are still rarely found.

AM processes can be classified into three different categories depending on the status of the material used to create the artefact during the process such as powder based, liquid based and solid based (Kruth et al.,1998). An overview is given in **Error! Reference source not found.**.

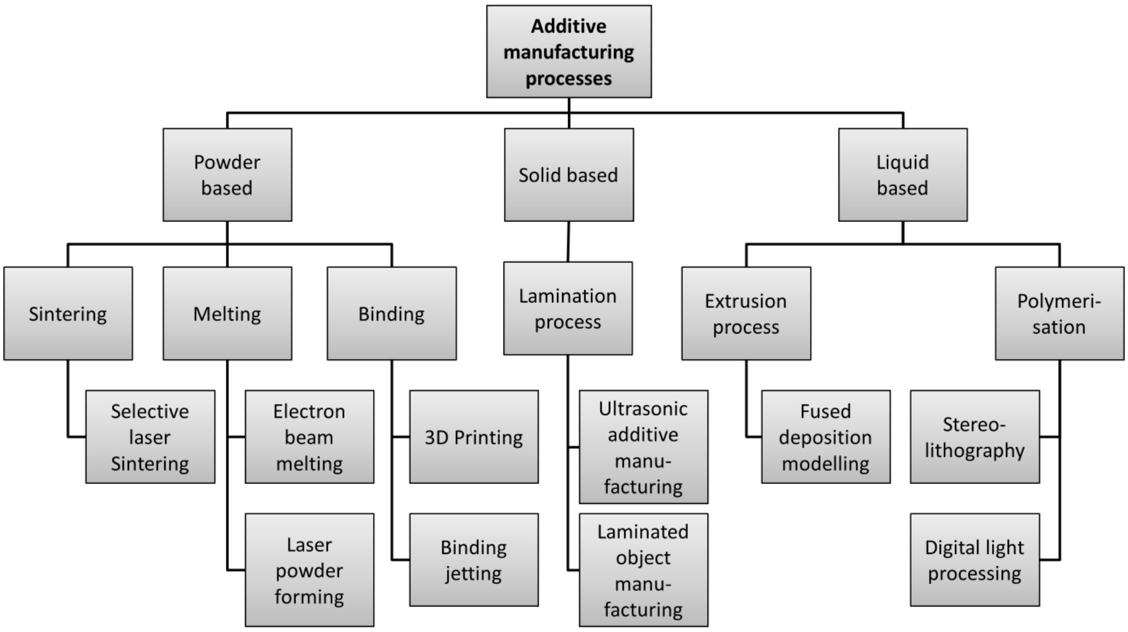


Figure 2: Classification of additive manufacturing processes (modified from Kruth et al. 1998)

Selective laser sintering (SLS), electron beam melting (EBM), laser powder forming (LPF), and binder jetting (BJ) are applicable for metals, for prototype and direct part manufacturing purposes. LPF is applicable for repair of parts and can thus extend the lifetime of a product even further. BJ's ability to produce complex sand casting moulds has the potential of design optimisation, where less material would be used in the mould. Ultrasonic additive manufacturing (UAM) and laminated object manufacturing (LOM) are suitable for metal artefacts, whereas LOM is additionally considered suited for paper and plastic artefacts. Since adhesive is used between layers, very little residual stresses are left in the artefacts. UAM's ability for interchangeable metals during the layering process offers opportunities for the production and repair of metal material of more than one type, such as bimetals where different coefficient of thermal expansion are required. Prototypical creations are mainly applied fused deposition modelling (FDM) for polymer based material and using stereo lithography (SL) and digital light processing (DLP) for photopolymer based material.

Since the equipment for AM was usually very expensive and rare, hardly such technologies were used for non-industrial applications. Due to the emergence of low cost and easy to use so called 3D printers, this situation changed dramatically. In 2004, Bowyer et al. (2013) founded the RepRap project for low cost 3D printers, which were followed by likewise initiatives. The ability to manufacture in a highly flexible manner almost any geometric form in one step offers the chance to apply AM within households.

The aforementioned enabling technologies basically allow increasing influence of consumers in value creation. However, the value creation is not supposed to be actively carried out by consumers, most of the times due to high transaction and equipment costs. Miniaturisation and innovation lead to small size machine tools for various applications. If equipment becomes sophisticated in performance with intuitive user interfaces, it may enter the customer domain. Equipment for so called desktop manufacturing offer the chance to make manufacturing a tool for everyday life purposes like the personal computer did with software before. Clearly, there are differences of DDM to the traditional manufacturing paradigms particularly in different roles of stakeholders involved in the manufacturing system which are presented in the next section.

3 Classification and comparison of manufacturing paradigms

Manufacturing paradigms are classified as follows. Craft production was traditionally carried out by experts through their skills and knowledge for a specialised task and the design of the product. The crafting skill is often honed through on-the-job-training, at a specialised workshop. The craftsmen would often produce a variety of products, but the products would share similarities, in the way they were produced. These craftsmen would have few consumers for their goods, mainly their local community but it was not unheard of that customer's requirements would be incorporated in the products. Mass production requires formal specialisation, where standardised products are manufactured in a large plant according to a specific design. Mass production includes internalisation of design requirements (mass production) where inexpensive products with high quality are produced. The product's consumers are large groups of passive consumers with little or none influence on the product's design. Products and the demand for products do not go hand in hand. Mass customisation shares many similarities to mass manufacturing, but the consumers have a voice in how the products are designed. The products are modularised or have been bespoken for specific segments of end users. These products have predetermined number of variants.

The design requirements of DDM are created by a number of different people. Once created these specific designs remain as catalogues to select which can be manufactured directly, improved or altered according to desire. The prosumer manufactures the personalised products for local demand with a technology with various benefits. The interconnectedness of those involved in the design and the design improvement is only restricted to the ability to interact. It is foreseeable that in some instances, a small group of end users would rely on one prosumer for their product demand, e.g. for pooling of manufacturing resources. The differences in terms of roles of actors involved in the manufacturing system are graphically compared as illustrated in Figure 3. This figure shows how the manufacturing paradigms have evolved with respect to the origin of design requirements, the number of design and manufacturing variants as well as the types of end users. As previously noted, craft manufacturing was the carried out by artisans (depicted in green colour) in a workshop for the product consumers (shown in dark red colour). In mass manufacturing product development is a separated task carried out by a designer (presented in violet colour). Manufacturing is carried out in a factory with specialised factory workers (indicated in blue colour). Consumers can select from standardised products. Mass customisation is very similar to mass manufacturing, but the consumers have a larger selection of goods, which can customised. DDM relieves the need for formal segmentation of specialisation and offers the possibility of quicker adaptation of products according to various design values (e.g. usefulness, performance, material selection and aesthetics). Table 1 shows a summarised overview of the characteristics of the manufacturing paradigms for design and manufacturing. It should be noted that DDM is not expected to substitute the already established manufacturing paradigms, but rather compliment them.

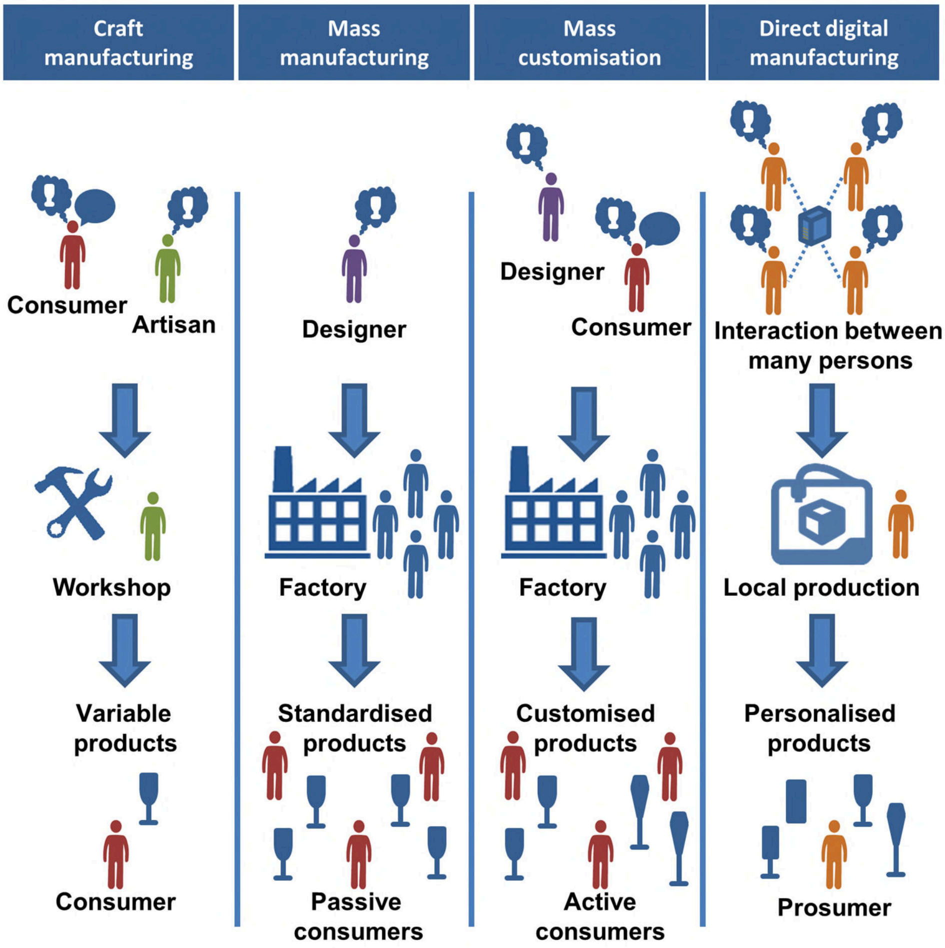


Figure 3: A comparison of manufacturing paradigms and their main actors (modified from Abel et al., 2011)

In table 1, the 'Who' stands for those responsible for the design and manufacturing, the 'How' represents how the design is passed between those responsible, 'Where' refers to the type of facility, 'What' refers to the product characteristics, 'How many' refers to the lot size and the end user is presented 'For whom'. It can be seen clearly that the DDM paradigm contains dematerialisation, demand driven design consideration, on-demand manufacturing and democratisation amongst others.

Table 1: Characteristics of manufacturing paradigms for design and manufacturing.

Description		Craft production	Mass production	Mass Customisation	Direct digital manufacturing
Design and manufacturing	Who	Craftsmen	Designers and specialists	Designers and specialists	Network of different people
	How	Experience based	Receive design	Receive design	Create and/or download design
	Where	In a workshops	In a factory	In a factory	On an AM machine
	What	Variable products	Standardised, high quality products	Standardised, high quality products with predetermined variants	Personalised and variable, high quality products
	How many	Lot size of one	In large batches	In small batches	Lot size of one
	For whom	Consumer (few to few)	Passive consumers (few to a large group)	Active consumers (few to many small groups)	Prosumer (Network to individuals)

On the whole, these variations can lead to different outcomes not only on the productivity of the manufacturing system but also for the environment and the entire society. A holistic view of the impacts of DDM is discussed further in the next section under the triple-bottom-line of the sustainability through a product life cycle point of view. This is to highlights the advantages and the disadvantages particularly the practicality on how well these manufacturing paradigms are suitable in the manufacturing system.

4 Sustainability and DDM

During a product development, many questions need to be considered such as how to design a product, how to manufacture a product, how to use a product, how to dispose (including recycle, reuse and remanufacturing) a product and in the best way how society will be effected by it. This means a product have different phases; design, manufacturing, use and disposal. All of these phases have different sustainability perspectives and indicators which need to be considered. In the end, final product and all these four phases will eventually affect society somehow.

From society perspective, one of the most common definitions of sustainability and sustainable development was provided by the Brundtland (1987) commission: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs". The aspects of sustainability are many, NIST (National Institute of Standards and Technology) have categorised them to environmental stewardship, economic growth, social well-being, technological advancement and performance management (Joung et al., 2012). But generally, sustainability have three common dimensions; social, economic and environmental dimensions. Where traditionally, economic aspects dominate decision making, with respect to sustainability, these dimensions should be considered simultaneously and equally (Seliger, 2007; Salonitis and Ball, 2013).

Traditionally in the manufacturing phase, the performance of a production system is assessed by monitoring four main classes of manufacturing attributes; namely cost, time, quality and flexibility. Nowadays however, additional issues must be considered, such as energy and resources efficiency that are apart of sustainability (Salonitis and Stavropoulos, 2013), see Figure 4. It is evident that sustainability has evolved to be a key manufacturing decision attribute that incorporates cost. In order to support later discussions on sustainability related implications of DDM, the next section provides an overview of the related sustainability indicators.

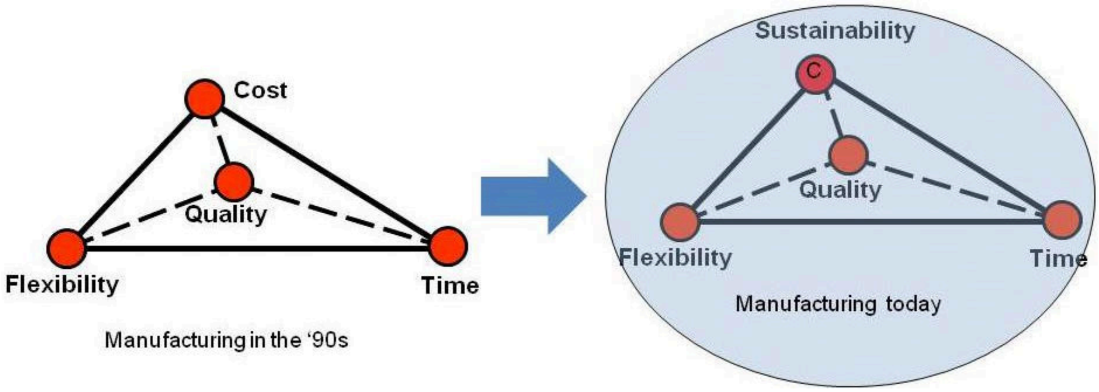


Figure 4: Manufacturing decision making attributes in 1990s and at present time (Salonitis and Stavropoulos, 2013).

4.1 Sustainability indicators

In order to evaluate the impact of the different manufacturing paradigms, it is necessary to use a join assessment basis. Depending on the viewpoint, sustainability may imply different meanings and it can be evaluated. Currently, there are many assessment tools to evaluate the sustainability (Chen et al., 2013). There are indicators and indices such as:

- Dow Jones Sustainability Index to evaluated company sustainability, most related to economical part of sustainability.

- GM Metrics for sustainable manufacturing developed for car industry.
- GRI Reporting Framework developed to evaluate company and factory.

Above, there are viewpoints for the manufacturing and the whole company. Another viewpoint is from society perspective developed by United Nations. The United Nations Commission for Sustainable Development (UNCSD) offers a breakdown structure for sustainability with 14 themes, 44 subthemes and 96 indicators (UN, 2007). According to the UNCSD, these indicators are supposed to cover the general topics of sustainable development, and are able to be derived from existing statistics (CSD, 2012). The acceptance and use of UNCSD indicators is voluntary. They are intended to provide a reference for the member states in their work of reviewing existing or developing new indicators. However, due to the voluntary character, no UN-wide accepted definition or assessment metrics for sustainable development is yet available (UN, 2012). The work from UNCSD involves the sustainability point of view from many countries which is a very good source to use. The main benefit to use and the interest to follow this work is the holistic view of sustainability at a society level. It has also been shown that this UN work can be adapted to a factory level and give a holistic view of what needs to be considered in manufacturing from the factory perspective, and compatible to the society level (Chen et al., 2012).

In theory, the traditional environmental indicators that are associated with human health, ecosystem and resource use damages can also be considered in a general perspective using certain methodology such as the life cycle assessment. For this paper, a number of important sustainability subthemes and indicators for manufacturing phase are summarised in Table 2. They are inspired by the UNCSD indicators and the previous study from Chen et al. (2012). According to this table, although only main relation is presented for each indicator, most of indicators have a thematic linkage due to the multi-dimensional nature of the sustainable development. Each subtheme can have more than one indicator but only few subthemes with few indicators are chosen to illustrate. For example noise and air impact are two important topics in sustainability but they are not directly mentioned in the table. However this does not imply that they are not included in the table. In general air and noise problem is already considered under the subtheme: “Working condition”, “Work’s impact on worker’s long term health” and “Impact on climate change”. Depends on what kinds of impact “air” gives, it will give different results which many of them are measurable and can be summarised under e.g., indicator “Number of work injury or fatalities per year in a factory”. Alternatively impact can also be shown under “Work’s impact on worker’s long term health” such as lung cancer. In some cases the impacts on “air” do not have to be dangerous for human directly but affect the climate change.

From the product development perspective, the sustainability indicators in the user phase are mostly qualitative instead of quantitative as in the manufacturing phase. The social sustainability indicators such as user friendly and customer satisfaction are important to take care of, even they are not easy to have a quantitative measurement of. The outcomes of these sustainability indicators are reviewed in the following subsection.

Table 2: Examples of the sustainability subthemes and indicators for manufacturing phase

Dimension	Subtheme	Indicator
Economic dimension		
	Energy use	Energy consumption [Tonnes of oil equivalent]: This indicator measures the level of energy use and reflects the energy use patterns. This indicator can be used in different level of manufacturing. It can be energy consumption e.g. per machine level or per process level. The energy can be in form of liquids, solids, gases and electricity.
	Material consumption	Material consumption per manufactured product [ton or kg]: This indicator provides an assessment of use of raw material and in this way accustoms an efficient use of resource.
	Waste management	Generation of waste [kg/category]: This indicator reflects the waste-generation patter and measures amount of waste generated by specific category e.g. activity, process or manufactured product. By having this patter or number, the main waste trend can be identified for each category, and in this way accustom a more efficient use of resource and energy.
	Profitability	Profitability per product: This indicators measures profitability per product based on some other important indicators/number which are manufacturing cost, labour cost, product material cost, equipment cost and product cost.
	Manufacturing costs	Manufacturing cost per article/product: This indicator reflects how efficient the manufacturing is planned by measure throughput time, process time and more.
Social dimension		
	Working condition	Number of work injury or fatalities [U] per year in a factory: All the direct injuries cost by safety issues such as missing safety fence of a machine and dangerous toxic gas.
	Work’s impact on worker’s	Number of long term injury [U] per year in a factory: This indicator takes all the long term injury such as depression, back pain and lung cancer.

	long term health	
	Employee turnover	The rate [%] at which the factory gains and losses employees. It is important to record and keep track of this number as too high employee turnover can reduce the factory's productivity.
	Proportion of permanent employees	The proportion [%] of permanent to non-subcontract employees at the factory. This number is important corporate responsibility factor as it indicates the factory's commitment towards its labour.
	Employee empowerment	The number [U] of vocational education and training seminars the factory offers to improve the employee qualification for their designated tasks and work.
Environmental dimension		
	Impact on climate change	Emission of carbon dioxide equivalent [tonnes]: This indicator measures how much a factory emits per year. This number is important to have in order to control the emission and impact on climate.
	Source of energy	The proportion [%] of energy the factory utilises of renewable energy. This number indicates the CO_2 burden the factory's energy has at when it enters the factory.
	Impact on water quality through radiation heat transfer	Emission of waste process heat [W] to process water. This number depicts how much heat is being transferred from the plant to the adjacent water source(s).
	Impact on water quality through solid waste	Amounts of solids (dissolved and un-dissolved) [kg] passing as process waste to adjacent water source(s).
	Impact on water and soil through acidification	Amount of acidifying compounds carried through process water [kg]. This number is important to in order to reduce the acidification pollution.

4.2 Sustainability related implications of DDM

Having in mind the evolution of manufacturing paradigms and the growing importance of sustainability, the question arises: which are the differences for DDM in comparison to traditional manufacturing paradigms? In relation to the indicators provided in the previous section, Table 3 summarises an overview for the sustainability implications of DDM relative to the other manufacturing paradigms based on existing literature/studies. It is also indicated whether the specific aspects of DDM tend to be rather: beneficial (+); unfavourable (-); or whether it cannot clearly be assessed for the general case (+/-).

Table 3: An overview for the implications of DDM on the sustainability dimensions

Economic	Environmental	Social

<table>
<tr>
<td colspan="2">▪ Higher material utilisation (+)
▪ Simpler, more efficient supply chains with less transportation efforts (+)
▪ Less material and energy losses due to less inventory (+)
▪ Less waste and better waste management through possibility of direct recycling (+)
▪ User oriented manufacturing, less over-production in stocks (+)
▪ No moulds etc. necessary (+)
▪ Higher specific energy demand (-)
▪ Quality issues are not finally solved, thus risk of bad parts and rework (-)</td>
<td rowspan="2">▪ equal possibilities to all participants in markets and societies (+)
▪ bridge technological, educational and cultural gaps between developing and developed countries (+)
▪ user oriented products, more customer satisfaction (+)
▪ potential benefits on human/worker health (+)
▪ unclear impact on an employment situation of industry (+/-)</td>
</tr>
<tr>
<td>▪ Potentially higher profit due to customer specific solutions (+)
▪ Profitability could be proved in selected cases (+/-)
▪ Longer manufacturing time (-)</td>
<td>▪ Ambivalent studies in terms of an environmental impact or eco-efficiency, (+/-)</td>
</tr>
</table>

Energy and material flows as a base for the economic and environmental assessments

Table 3 underlines that specifically the economic and environmental dimensions are strongly connected. DDM induces changes in energy and material flows of value chains. Through conversion with monetary (economic) or environmentally related factors (e.g. global warming potential), the impact in each dimension can be calculated.

Mellor et al. (2013) proposed a generic framework for implementing DDM that portrayed the necessity in considering supply chain, manufacturing system, strategy and organisation change for different DDM technologies. One of the suggestions is to decentralise in order to reduce the impact from the transportation and also to support the local communities. As several authors state DDM has a waste reduction potential through higher efficiency in raw material utilisation, i.e. dematerialisation as well as through on-demand potential due to closeness to the consumer, resulting in less pollution and less energy consumption (Campbell, 2011). Due to more decentralised value chains and more user orientation, DDM also reduces the need for inventorying, which in terms represents energy and material savings for storage and less number of degraded products. DDM also involves less and/or less complex tools for processing (e.g. mould) which again potentially leads to energy and material savings. Besides studies focusing on material efficiency, for the process itself various studies also investigated the energy demand of DDM. While this is a complex field with ambivalent results depending on the specific process and conditions, a detailed case study was conducted on this issue and is described in section 6.

The main findings from the previous studies that are associated with the sustainability indicators in Table 2 are discussed in detail as follows.

Economic dimension

Some authors investigated in more detail the economic potentials of DDM. For example, through DDM the users have access to a global community, where designs flow almost within an instance to the DDM equipment, reducing development time and rendering complex supply chains less important as the focus would be on raw materials (Campbell et al., 2011; Bauwens et al., 2012). On the other side, DDM has unsolved issues such as certification rules when manufacturing become more democratised, quality problem due to the low tolerances, as well as material and processing capabilities need also to be improved.

Energy and material consumption are indicators for DDM that have been investigated by various studies. Baumers et al. (2012) used activity-based costing (ABC) method proposed by Ruffo et al. (2006) to estimate the financial cost modeling of the raw material and energy costs. They found that a wide variety of parts are more likely to improve economics of DDM as well as reducing the energy consumption when investigating six products that had different dimensions and complexities. Atzeni and Salmi (2012) found that DDM, such as direct metal laser sintering (DMLS), can compete with the high pressure die-cast process for a small to medium batch of end-usable metal parts. DMLS is cheaper than the traditional process which often has lower mould cost at the high production volume.

Wittbrodt et al. (2013) conducted a comprehensive study for the economic indicator of DDM by considering the entire life cycle using an open-source 3-D printer, RepRaps as a case study for PLA technology. They calculated it based on a product price for the material and production cost (US$ 399 - 2,199) and operating cost across its lifetime. At the conservative assumption of 20% fail rates, 20 product per year and 25 hours per product, they found that the return of investment (ROI) of PLA is higher than the traditional manufacturing practice by approximately >200% to >40% which is equivalent to a pay back period of 4 months to 2 years. The main cost elements are the shipping, the energy and the filament consumptions during the operation. This is owing to the high energy intensity that is required for the extrusion and the preheat process of PLA which depends highly on the mass and printing time.

The waste management is also another good economic indicator of DDM that often is discussed in a waste reduction context (Khajavi et al., 2014; Cozmei et al., 2012; Holmström et al. 2010). Wittbrodt et al. (2013) found that one of the benefits of the 3-D printer is to manage wastes produced from bad prints by allowing user to recycle and converting them into filament, which effectively reduce the filament cost.

The profitability indicator was the last economic indicator which was investigated in many contexts. Hopkinson and Dickens (2003) compared the machine, material and labour costs for two complex parts with different geometry made of stereo-lithography (SL), selective laser sintering (SLS) and fused deposition modelling (FDM) with the injection moulding parts. DDM can compete with injection moulding at a higher production volume. Ruffo et al. (2006) developed another cost model that is suitable for low production volume using ABC. The model included the relevant profitability factors namely the direct and indirect costs, working time, manufacturing time, mass units and mass of the planned production. They found that DDM can provide cost-effective solution for the mixed production which manufactures more than one component in one machine.

Environmental dimension

According to the environmental indicators listed in Table 2, the total environmental impact (a single score), emissions of the greenhouse gas emission in carbon dioxide equivalent and sources of energy are often found in a number of studies. The single score, which has a unit of points, considers the traditional environmental damage to human health, ecosystem quality and resource use from released emission substances and the toxicity to air, water and soil of material types and quantities generally energy consumed during processing. No studies were found individually investigating the impact on the water quality and acidification.

For instance, Sreenivasan et al. (2010) compared the power consumptions of different SLS technologies in terms of eco-indicator. SLS found to be 8.3 times higher than other DDM processes. DDM can reduce carbon footprint by reducing: raw materials; energy intensive and wasteful process such as casting; fuel consumption from transport-related product and reduce distance of parts to the consumer location. Serres et al. (2011) conducted LCA for each step of direct additive laser manufacturing and found that it has 80% less single score value than machining process due to the absence of chips production. Atomisation is the major cause of the environmental impact as it is used for powder elaboration process.

Bourhis et al. (2013) calculated the massive energy use during the process in kWh per kg and a single score of an environmental impact value based on the Eco-indicator 99 in milipoints (mPts) per kg for different laser-based manufacturing machines. The minimum and maximum values are found in 5.4 to 346.4 kWh per kg and 3 to 197 points per kg one of SLS and FDM machines respectively.

For the indicators of the energy source and the carbon dioxide equivalent, Morrow et al. (2007) compared data from literature of the specific energy consumption (SEC) in kWh/kg and the amount of air pollutants in g/kg for different traditional manufacturing processes and the direct metal deposition (DMD) used in producing a tool steel. An atomisation process has the lowest value and DMD has the highest value. DMD can particularly help to reduce emissions and energy for remanufacturing valuable tools and dies. This is due to the fact that DMD can minimise energy consumption at the low ratios of the solid to cavity volume when compared to CNC milling which can minimise the energy consumption at the high ratios. Bourhis et al. (2013) and Morrow et al. (2007) concluded that an alternative material may require less materials but it could obtain higher embodied energy. This is because a new supplier may utilise higher transportation and their electricity mix may generate from higher embodied energy sources. This will lead to high carbon dioxide emission as well as shift to new emission substances due to different chemical compositions. Due to its strong relevance and interesting differences, a more detailed comparison of DDM (here SLS) and traditional manufacturing (injection moulding) can be found in section 6.

Social dimension

From a social perspective, democratised production enables equal possibilities to all participants in markets and society (Borghesi et al., 2008; Malone and Lipson, 2007; Mota, 2011). It is foreseeable that the entry barriers of becoming an active member of a value creation through manufacturing of goods are reduced down by the cost decrease of the system, additionally if the knowledge and skills required become less comprehensive than those of modern manufacturing systems or easily obtainable, then this democratisation is propelled even further. The DDM's forerunner of 3D printing has proven it relevance for research and educational purposes (Moilanen and Váden, 2012) and depending on the openness of the system and its infrastructure, the inclusion of developing countries is enabled as open innovation, especially open source hardware is able to bridge technological, educational and cultural gaps between developing and developed countries (Salem and Khatib, 2004). The impact on society needs to be investigated when traditional manufacturing successive become DDM, when traditional factory disappears. How society will reflect the change in terms of economy, lifestyle and environmental impact and more.

As a consequence, due to the complexity of the assessment for this social dimension, a limited number of studies are found. On this occasion, only the work condition and impact on worker's long term health are the social indicators discussed in Huang et al. (2013). They conducted a review of the societal impact of additive manufacturing from a technical perspective. They found that DDM has a health benefit when compared to the conventional processes such as casting, forging, and machining in terms of avoiding long-term exposure of noise hazardous and oil mist from metal working fluid. However, there are unknown DDM toxicological and environmental hazards which can be occurred due to handling, using, and the disposal of the materials used in the DDM processes. Such impacts can be minimised by reducing the amount of raw materials or even the auxiliary such as lubricants and changing to alternative materials. Moreover, the laser-based DDM machine is also required to be operated using safety equipment such as masks and goggles.

5 Energy use in production - DDM compared to mass production

Whereas the last chapter gave a general overview on sustainability related implications of direct digital manufacturing, this section focuses on specific life cycle phases and dimensions of sustainability with a case study regarding energy use in a production.

As indicated in section 5.2, energy use is one of the important indicators for sustainability. It can be directly related to both economic and environmental perspectives. This section aims to analyse it in detail for the production induced energy use of DDM in comparison to the mass production using a generic case study. The analysis compares two processes used for producing plastic parts. They are the selective laser sintering (SLS) representing a typical DDM related process and injection moulding (IM) as the mass production oriented process.

An extensive literature review was conducted and revealed that there are diverse references analysing the energy demand of processes including SLS, IM and related technologies. The specific energy demand per kg final product is commonly used to enable the comparability. Figure 5 presents the specific energy demand per kg of part produced for SLS, 3D printing (FDM – fused deposition modelling) and IM based on literature review.

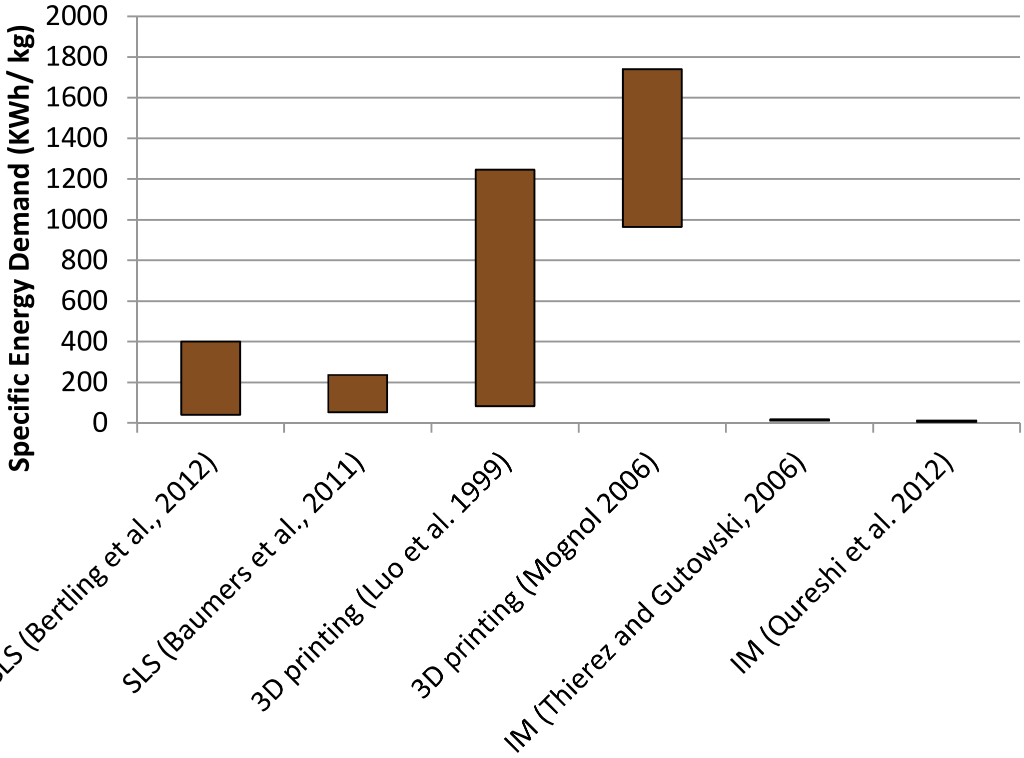


Figure 5: A comparison of energy demand per kg of part produced by different manufacturing processes

Resulting values in Figure 5 are widely spread due to the individual experimental settings (machine, product and process characteristics) and circumstances. For both SLS and IM (besides the machine itself) the speed/process rate has specifically a major influence on the specific energy demand (Qureshi et al., 2012; Baumers et al., 2011). However, the values clearly show that - for the process itself – even with just considering the order of magnitude, SLS is significantly more energy intensive than IM. SLS and IM show quite different composition of energy demand when distinguishing power and time. This can be shown with an energy portfolio (Thiede, 2012) and is qualitatively illustrated in Figure 6. IM has typically a rather short process time, often less than a minute, but requires relatively higher power demand for the machine to operate. In contrast, SLS and 3D printing processes take much longer time, several hours, while demanding less power. Having in mind the comparison of the specific energy demand values in Figure 5, it gets clear that the impact of the process time demand clearly dominates and leads to significantly a higher energy intensity of SLS and 3D printing. It is important to have in mind that SLS and 3D printing energy demand can also differ significantly – however, in a qualitative comparison to IM, both processes show similar characteristics.

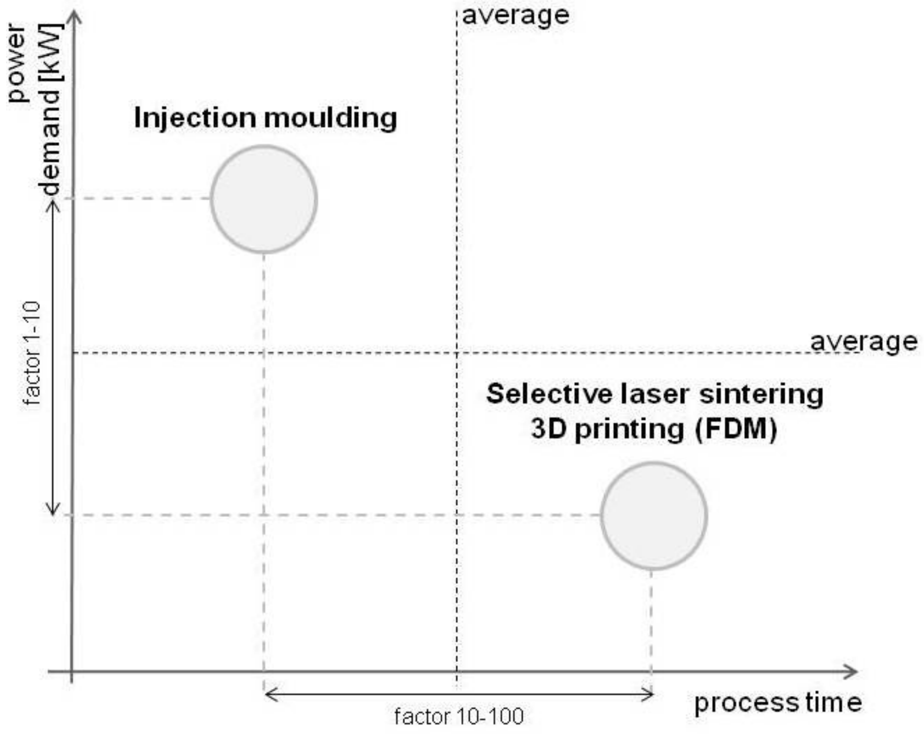


Figure 6: Qualitative illustration of energy portfolio for IM and SLS and process time

However, the energy demand of the process itself is just one perspective; other effects need to be taken into a consideration as well since they indirectly influence the energy demand of DDM from the system perspective (Hao et al., 2010; Sreenivasan, 2010; Reeves, 2008):

- *Material yields (ratio of final product weight and necessary input material weight)*: injection moulding demands additional material for gating systems, sprue or spillover which needs to be processed as well. In combination with relatively high reject rates, up to 50% of material was processed without value addition (Olmstaed and Davis, 2001) but it can be recycled in most cases. SLS (at least theoretically) literally focuses on the material which embodies the final product. However, studies underline that also for SLS not all of the remaining powder can be used again because it degrades over time. Material yields range from 56 to 80% (Telenko and Seepersad, 2010). From energy use perspective, the material yield is important to consider because it increases increasing energy demand (non value adding material processing) and is for additional recycling.

- *Necessary tools/mould*: While not required for SLS, IM needs product specific moulds to enable the process. Moulds often have complex geometries which can cause significant effort for development and production. This results in an additional energy demand in the pre-chain. According to Nopparat et al. (2012), mould's related energy demand sums up to about approximately 579 kWh or 2,084 MJ for a steel mould.
- *Complexity and individuality of parts*: in comparison to IM, DDM in general allows the production of more complex and individual parts. From the energy use perspective, this could result in potential benefits from a broader perspective. On one hand, DDM might integrate several steps into one process of the production therefore less machines and less energy are used. On the other hand, from a life cycle perspective, DDM enables i.e. more lightweight structures therefore higher energy input in the manufacturing phase might pay off due to less energy demand in the use phase. In any cases, it gets clearer that this cannot be assessed in general but always the very specific case needs to be taken into account.
- *Supply chain and transportation effects*: going beyond the production process itself, DDM has the potential to bring the right products into the right amount closer to the customers, thus energy demand for transportation and logistics in general might be decreased.

The previous points underline that an integrated perspective is necessary in order to balance benefits and drawbacks and to identify the optimal solution for a specific case. While focusing on the production related energy use, Figure 7 shows a trade-off analysis based on sample values given in the literature. The starting point on the y-axis is determined by an energy input of the pre-chain - in the case of IM the necessary mould needs to be incorporated there. The slope is determined by the energy intensity of SLS and IM respectively and the ratio of the material input to the weight output (of the final product). The analysis underlines that from an energy perspective, SLS is favourable for small production volumes but less appropriate for large volumes. There are no real economies of scale – even with larger volumes the specific energy demand (per kg) is constant for SLS whereas significantly decreasing for IM. Not only an energy perspective should be considered for the economic dimension, other variables of the economic dimension are also need to be additionally considered. For instance, a lower energy consumption is used to produce e.g. 30 kg of products is beneficial with SLS, however, it is important to take the process time into account where SLS take significantly substantially longer than IM.

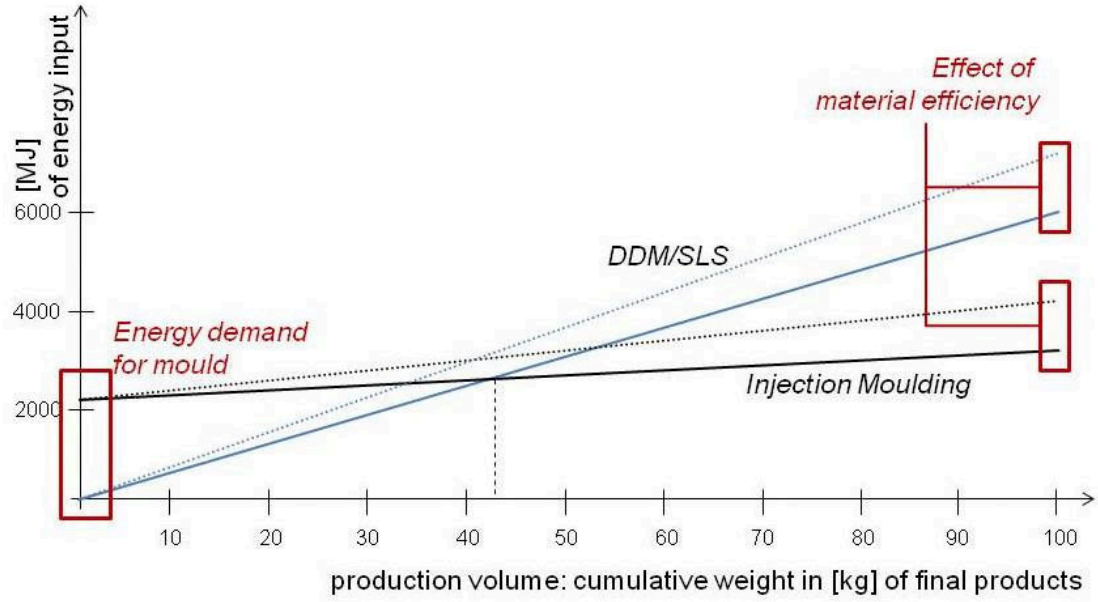


Figure 7: A trade-off analysis of injection moulding (IM) and selective laser sintering (SLS)

It is thus evident that in order to compare the manufacturing products in a more holistic way, the energy consumption of the main manufacturing machine is a necessary but not sufficient input value. In order to consider more aspects of energy demand, the idea of the embodied energy of the product after the final dispatching to the customer can be used, as it accounts for all necessary manufacturing processes and operations and not only one specific process. The embodied energy is basically the accumulated energy consumed for the production of any product, considered as if that energy was incorporated or 'embodied' in the product itself. It is an accounting approach that aims in finding the sum of the total energy that is necessary for an entire product life-cycle which means considering the energy consumed for the extraction, processing and transportation of the raw materials.

In the case of IM, the embodied energy comes from the material pre-processing (for example grinding of the material), the manufacturing of tools, mould and their maintenance, the energy consumed by the process itself etc. On the other hand for the case of SLS, the material preparation, the energy requirements for the production of the consumables (laser, support material etc), the energy consumed by the process etc. needs to be considered. The comparison accuracy depends largely on the system boundaries of the analysis. Figure 8 compares the embodied energy for a product produced by SLS and IM. An expected result reflects that embodied energy of the IM produced parts is a function of the expected batch size. At the lower batch size, SLS has lower embodied energy than that of the IM but not at the higher the batch size where the embodied energy of IM is less than half of SLS.

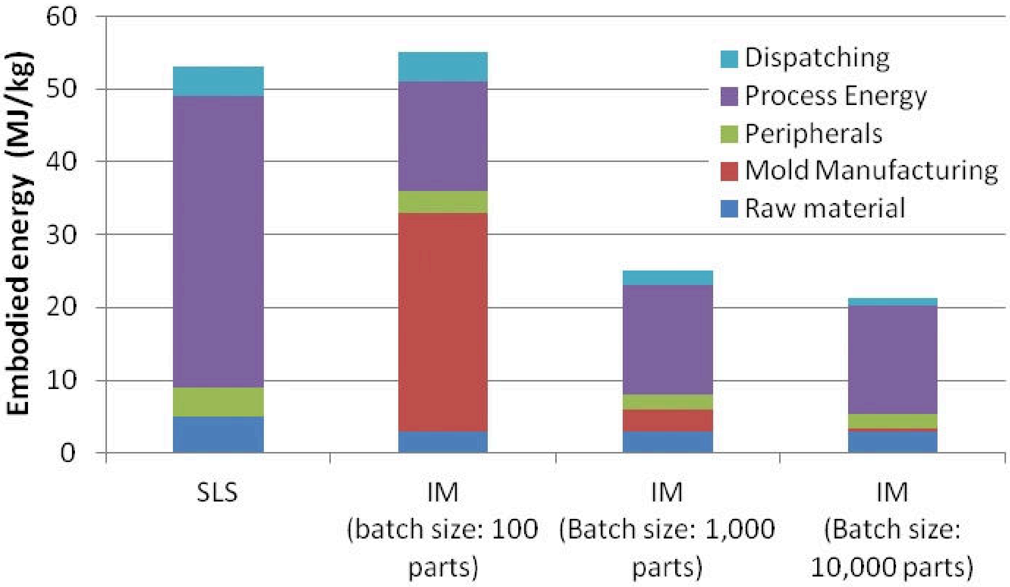


Figure 8: A comparison of embodied energy for SLS and IM produced products

6 Discussion and Conclusions

This paper presents an overview of DDM including historical background, classification, possible sustainability indicators and related sustainability research. In this work DDM is assumed as the latest production paradigm and it characteristics are compared with three well-established production paradigms. Different production levels and product phases have been analysed. A detailed case study about the energy use in mass production and DDM has been carried out to demonstrate the difference in depth.

According to this research, DDM seems to have a promising future, especially 3D printing. DDM has the possibility to combine the advantages of the production paradigms into personalised high quality products with the batch size of one. High skill would not be necessarily as the digitalisation enables online skill acquisition. Basic computer skill empowers the user to become its own manufacturer, generating local value at best with resources that are locally available. 3D printers have long shown their fit to bridge technological and educational gaps for people, and it is foreseeable that DDM is a good candidate to bridge technological, educational and cultural gaps between developing and developed countries. As DDM is dependent on the prosumer, products are produced closer to the point in time for when they are needed, resulting in less need for storage. Currently, the DDM technology is battling with two topics, firstly, the gathering a critical mass of contributors. Secondly, with the technological maturity, since the output quality is below adequate standard. Yet, the development of physical goods comes with several challenges.

As DDM relies on a community of people that are supposed to carry out the development, interoperability between the designer and the DDM equipments becomes a time issue. Currently, there is no standard to support this challenge. DDM requires calibration and physical tests to evaluate potential solutions, which in turn calls for an investment in hardware. Furthermore, the products themselves have to be tested for quality and combined with a high scrap rate, leading to increased material costs in a different way. As DDM enables the manufacturing of batch size one with digitalised skill acquisition, broader spectrum of users is empowered with the possibility of producing any products, one can imagine. Such actions can lead to increased material consumption and therefore environmental issues. As the capability of DDM to work on smaller scales improves, towards molecular level, the recyclability of the products produced with DDM becomes more difficult. Furthermore, the unknown toxicological and environmental hazards of DDM are also important to be investigated further. This is to prevent health and ecosystem damages caused by handling, using, and the disposal of the materials used in the DDM processes. DDM is proven to enable the supports for the growing trend of the personalised products as the society’s economy and life style changes. Social challenges can emerge in both micro and macroeconomic levels beyond the satisfaction of the customers. The social impacts that are particularly essential to be investigated include job losses, work safety, logistics, and waste management. Utilizing DDM for the production of goods that are then sold on a free market raises several questions such as product performance and reliability. From an European point of view, declaring a conformity for products manufactured under the conditions of DDM would be an arduous tasks, since it would be very unclear who designed what, especially if the design is carried out under a commercial collection use of creative commons, a framework that seems to be applicable as an enabler for DDM.

Acknowledgement

This joint research is a collaboration of the CIRP Research Affiliate working group, “Sustainable Factories”. All authors have equally contributed to this publication.

References

Abel B.V., Evers L., Klaassen R., Troxler P. (2011) Open design Now – Why design cannot remain exclusive. Bis Publishers.

Atzeni E., Salmi A. (2012) Economics of additive manufacturing for end-usable metal parts. International Journal of Advanced Manufacturing Technology 62 (9), pp. 1147–1155.

Baumers M., Tuck C., Wildman R., Ashcroft I., Hague R. (2011) Energy inputs to additive manufacturing: Does Capacity utilization matter?, in: Solid Freeform Fabrication Proceedings - an additive manufacturing conference, Austin, USA, pp. 30-40.

Baumers M., Tuck C., Wildman R., Ashcroft I., Rosamond E., Hague. R. (2012) Transparency built-in energy consumption and cost estimation for additive manufacturing. Journal of Industrial Ecology 17(3), pp. 418-431.

Bauwens M., Iacomella F., Mendoza N. (2012) Report: A Synthetic Overview of the Collaborative Economy, Orange Labs and P2P Foundation. Retrieved online from: http://p2p.coop/files/reports/collaborative-economy-2012.pdf

Baumers, M., Tuck, C., Bourell, D. L., Sreenivasan, R., & Hague, R. (2011). Sustainability of additive manufacturing: measuring the energy consumption of the laser sintering process. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 225(12), 2228-2239.

Bertling, J., Blömer, J., Rechberger, M., Schreiner, S. (2012) DDM – An Approach Towards Sustainable Production?, Fraunhofer Direct Digital Manufacturing Conference 2012.

Borghesi S., Vercelli A., Vercelli A., (2008) Global Sustainability: Social and Environmental Conditions, Basingstoke England: Palgrave Macmillan.

Bowyer A. et al. (2013) Retrieved online from: http://adrianbowyer.net/

Bourhis Le F., Kerbrat O., Hascoet J-Y., Mognol P. (2013), Sustainable manufacturing: evaluation and modelling of environmental impacts in additive manufacturing. International Journal of Advanced Manufacturing Technology 69, pp. 1927-1939.

Brundtland G.H. (1987) Our common future. Oxford: Oxford University Press.

Campbell T., Williams C., Ivanova O. and Garrett B. (2011) Could 3D Printing Change the World? Technologies, Potential, and Implications of Additive Manufacturing. Strategic Foresight Initiative, Atlantic Council. (Retrieved online from: https://info.aiaa.org/SC/ETC/MS%20SubCommittee/Alice%20Chow_3D%20Printing%20Change%20the%20World_April%202012.pdf)

Chen D., Schudeleit T., Posselt G., Thiede S. (2013) A state-of-the-art review and evaluation of tools for factory sustainability assessment, 2nd CIRP Global Web Conference

Chen D., Heyer S., Seliger G., Kjellberg T. (2012) Integrating sustainability within the factory planning process, CIRP Annals - Manufacturing Technology, 61(1), 463–466.

Cozmei C., Caloian F., (2012). Additive Manufacturing Flickering at the Beginning of Existence. Procedia Economics and Finance 3, pp. 457–462.

CSD, 2012. CSD Indicators of Sustainable Development – 3rd edition, The United Nations Division for Sustainable Development.

Duflou J.R., Sutherland, J. W., Dornfeld, D., Herrmann, C., Jeswiet, J., Kara, S., Hauschild, M., Kellens, K. (2012).Towards energy and resource efficient manufacturing: A processes and systems approach. CIRP Annals - Manufacturing Technology, 61(2), 587-609.

Gibson I., Rosen D.W., and Stucker B. (2010) Additive Manufacturing Technologies – Rapid Prototyping to Direct Digital Manufacturing, Springer

Hao L., Raymond D., Strano G., Dadbakhsh S. (2010) Enhancing the Sustainability of Additive Manufacturing. In: ICRM2010-Green Manufacturing, Ningbo, China, 390-395.

Holmström J., Partanen J., Tuomi J., Walter M. (2010). Rapid manufacturing in the spare parts supply chain: alternative approaches to capacity deployment. Journal of Manufacturing Technology Management 21(6), 687–697.

Hopkinson N., Dickens P. (2003) Analysis of rapid manufacturing– using layer manufacturing processes for production. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 217(1), 31-39.

Huang S.H., Liu P., Mokasdar A., Hou L. (2013) Additive manufacturing and its societal impact: a literature review. The International Journal of Advanced Manufacturing Technology 67, pp. 1191-1203.

Ibbotson S., Kara S. (2014). LCA case study. Part 2: environmental footprint and carbon tax of cradle-to-gate for composite and stainless steel I-beams. The International Journal of Life Cycle Assessment, 19(2), 272-284.

Ibbotson S., Dettmer T., Kara S., Herrmann C. (2013). Eco-efficiency of disposable and reusable surgical instruments—a scissors case. The International Journal of Life Cycle Assessment. 18(5), 1137-1148.

Joseph Pine B. (1993). Mass Customization: The New Frontier in Business Competition. Harvard Business Press.

Joung C.B., Carrell J., Sarkar P., Feng S.C. (2012) Categorization of indicators for sustainable manufacturing. Ecological Indicators 24, pp. 148–157.

Khajavi S.H., Partanen J., Holmstrom J., (2014). Additive manufacturing in the spare parts supply chain. Computers in Industry 65, pp. 50-63.

Kunnari E., Valkama J., Keskinen M., Mansikkamaki P., (2009) Environmental evaluation of new technology: printed electronics case study. Journal of Cleaner Production. 17, 791–799.

Kruth J.-P., Leu M.C., Nakagawa T. (1998) Progress in Additive manufacturing and rapid prototyping, CIRP Annals - Manufacturing technology, 47(2), 525-540.

Li W., Winter M., Kara S., Herrmann C., (2012), Eco-efficiency of Manufacturing Processes: A Grinding Case, *CIRP Annals – Manufacturing Technology*, 61(1), 59-63.

Luo, Y., Ji, Z., Leu, M. C., & Caudill, R. (1999). Environmental performance analysis of solid freedom fabrication processes. In Electronics and the Environment, 1999. ISEE-1999. Proceedings of the 1999 IEEE International Symposium on (pp. 1-6). IEEE.

Malone E., Lipson H. (2007) Fab@Home: The Personal Desktop Fabricator Kit. Rapid Prototyping Journal, 13(4), pp. 245-255.

Manmek S., Kaebernick H., Kara S. (2010), Simplified Environmental Impact Drivers for Product Life Cycle, International Journal of Sustainable Manufacturing, 2(1), 30-65.

Mellor S., Hao L., Zhang D. (2013) Additive manufacturing: A framework for implementation. International Journal of Production Economics, In press.

Mognol, Pascal, Denis Lepicart, and Nicolas Perry. "Rapid prototyping: energy and environment in the spotlight." Rapid Prototyping Journal 12.1 (2006): 26-34.

Moilanen J., Vadén T. (2012) Manufacturing in Motion: First Survey on 3D Printing Community. Retrieved online from http://surveys.peerproduction.net/2012/05/manufacturing-inmotion/

MoosaviRad S.H., Kara, S., Ibbotson S. (2013). Evaluating CO2 Emissions Associated With International Outsourcing in Manufacturing Supply Chains, Modern Applied Science. 7(10)

Morrow W.R., Qi H., Kim I., Mazumder J., Skerlos S.J. (2007) Environmental aspects of laser-based and conventional tool and die manufacturing. Journal of Cleaner Production 15(10), pp. 932–943.

Mota C. (2011). The rise of personal fabrication. Proceedings of the 8th ACM conference on Creativity and cognition - C&C ’11, 279. doi:10.1145/2069618.2069665

Nopparat, Nanond and Kianian, Babak (2012): Resource consumption of Additive manufacturing technology, Thesis submitted for completion of Master of Sustainable Product-Service System Innovation (MSPI), Blekinge Institute of Technology, Karlskrona, Sweden.

Olmstaed B., Davis M. (2001) Practical Injection Molding, Marcel Dekker, Inc., NY.

Qureshi F., Li W., Kara S., Herrmann C. (2012) Unit Process Energy Consumption Models for Material Addition Processes: A Case of the Injection Molding Process. In Leveraging Technology for a Sustainable World (pp. 269-274).

Reeves P. (2008) Additive Manufacturing – A supply chain wide response to economic uncertainty and environmental sustainability, Econolyst Limited, The Silversmiths, UK.

Ruffo M., Tuck C., Hague R. (2006) Cost estimation for rapid manufacturing – laser sintering production for low to medium volumes. Proceedings of IMech E Part B: Journal of Engineering Manufacture 220(9), 1417-1427.

Salem M. A., Khatib J. I. (2004), An Introduction to Open-Source Hardware Development, EETimes. Retrieved online at: http://eetimes.com/electronics-ews/4155052/Anintroduction-to-open-source-hardware-development

Salonitis K., Ball P. (2013) Energy efficient manufacturing from machine tools to manufacturing systems, Procedia CIRP 9, pp. 634 – 639.

Salonitis K., Stavropoulos P. (2013) On the integration of the CAx systems towards sustainable production, Procedia CIRP 9, pp. 115-120.

Salonitis K. (2014) 10.03 Stereolithography. In: Saleem Hashmi (ed.): Comprehensive Materials Processing. Volume 10: Advances in Additive Manufacturing and Tooling, pp. 19-67. Elsevier, 2014.

Seliger G. (2007) Sustainability in manufacturing recovery of resources in product and material cycles, Springer, Berlin

Serres N., Tidu D., Sankare S., Hlawka F. (2011) Environmental comparison of MESO-CLAD process and conventional machining implementing life cycle assessment. Journal of Cleaner Production 19, pp. 1117–1124.

Sreenivasan R., Goel A., Bourell D.L. (2010) Sustainability issues in laser-based additive manufacturing. Physics Procedia, 5, 81-90.

Telenko C., Seepersad C.C. (2010). Assessing Energy Requirements and Material Flows of Selective Laser Sintering of Nylon Parts. In Proceedings of the Solid Freeform Fabrication Symposium 2010 (pp. 8-10).

Thiede, S. (2012). Energy efficiency in manufacturing systems. Springer.

Thiriez, A., & Gutowski, T. (2006, May). An environmental analysis of injection molding. In Electronics and the Environment, 2006. Proceedings of the 2006 IEEE International Symposium on (pp. 195-200). IEEE.

Umeda, Y., Takata, S., Kimura, F., Tomiyama, T., Sutherland, J. W., Kara, S., Herrmann, C., Duflou J. R., 2012, Toward integrated product and process life cycle planning—An environmental perspective, CIRP Annals - Manufacturing Technology, 61(2), 681–702.

United Nations, 2007, Indicators of sustainable development: guidelines and methodologies, United Nations publication, ISBN 978-92-1-104577-2

United Nations (2012) RIO 2012 Issues Briefs No. 6, UNCSD Secretariat, Rio+20 UNCSD

Vinodh, S., (2010). Improvement of agility and sustainability: A case study in an Indian rotary switches manufacturing organisation. Journal of Cleaner Production 18, 1015-1020.

Wittbrodt B.T., Glover A.G., Laureto J., Anzalone G.C., Oppliger D., Irwind J.L., Pearce J.M. (2013). Life-cycle economic analysis of distributed manufacturing with open-source 3-D printers. Mechatronics 23, pp. 713-726.

Womack J.P., Jones D.T., Roos D. (2007). The Machine that changed the world. Free Press, NY

Cranfield University

CERES https://dspace.lib.cranfield.ac.uk

School of Aerospace, Transport and Manufacturing (SATM) Staff publications (SATM)

2015-09-30

Direct digital manufacturing: definition, evolution, and sustainability implications

Chen, Danfang

Elsevier

Chen D, Heyer S, Ibbotson S, et al., (2015) Direct digital manufacturing: definition, evolution, and sustainability implications. Journal of Cleaner Production. Volume 107, November 2015, pp. 615-625

https://doi.org/10.1016/j.jclepro.2015.05.009

Downloaded from Cranfield Library Services E-Repository