Chapter

A Sustainability Assessment of Smart Innovations for Mass Production, Mass Customisation and Direct Digital Manufacturing

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Abstract

Smart production innovations are set to revolutionise manufacturing, yet little is known about their impact on sustainability. This chapter focuses on the evaluation of production innovations related to Industry 4.0 that may make products and processes more sustainable or less sustainable based on the application in different production systems. A review of current literature and use of sustainability hierarchies finds that, in the environmental dimension, mass production would benefit most from the introduction of a pull principle whereas for mass customization, machine to machine communication is recommended. The use of augmented reality is indicated as an asset to the sustainability of direct digital manufacturing. Results including the environmental, social and economic dimensions of sustainability are confirmed using value analysis.

Keywords: sustainable manufacturing, Industry 4.0, direct digital manufacturing, mass production, mass customisation

1. Introduction

The three main production methods are mass production (also known as flow production or continuous production), job production and batch production. Job production is custom work characteristic of craft production. Batch production makes specified groups or amounts of products so that changes in material or detail can happen between batches. Very small batch sizes are characteristic of mass customization.

Craft production dominated manufacturing prior to the mid-nineteenth century. Competitive priorities included cost and quality with low volume output, agility and individualised products. Craft, however, became unable to satisfy growing market demand, lost connection with industrial progress, and could not compete as identity and local uniqueness fell out of favour with the rise of low-cost mass production [1].

The first machine tools for mass production were developed in Britain in the mid-eighteenth century. These included precision lathes and measuring instruments such as the bench micrometre. Machine tool technology made it possible to have interchangeable parts, and this enabled mass production. The concept of mass production was refined by Henry Ford in the early twentieth century with the introduction of the moving belt assembly line. Mass production uses special-purpose machines for efficient high-volume production at the expense of flexibility [2].

The term 'mass customization' was introduced as 'companies try to reach the same large segment of customers in the market but by treating them individually like a customized market' [3]. The main characteristics of mass customization are variety that meets customer needs with prices comparable to mass production [4, 5].

Mass customization aims to provide personalised products in an industrial environment. With the introduction of Industry 4.0, mass customization is gaining popularity. Big data applications may provide insight into customer preferences and optimise current manufacturing configurations [6]. However, mass customization is associated with additional costs and end-of-life issues when compared to mass production.

Direct digital manufacturing (DDM) combines product modelling and manufacturing technology to eliminate the need for tooling as digital models are converted directly into physical objects [7]. The exploitation of DDM for mass production or mass customization is only just starting to be explored [8]. The new manufacturing paradigm of DDM comes with sustainability concerns that have not been fully investigated.

Industry 4.0 consists of four design principles: interconnection, information transparency, technical assistance and decentralised decisions. The Industry 4.0 production innovations that will be investigated are cobots (physical assistant systems), machine-to-machine communication (M2M), radio frequency identification (RFID) and near-field communication (NFC) technology, quick response (QR) codes, augmented reality, mobile devices, condition monitoring/predictive maintenance, production based on the pull principle, intelligent resource management connecting machines and plants, and localised sourcing of parts.

This chapter connects Industry 4.0 innovations with mass production, mass customization and DDM to optimise their sustainability in the environmental, social and economic dimensions. A literature review of mass production, mass customization and DDM is followed by analysis of Industry 4.0 innovations using manufacturer sustainability needs hierarchies. Value analysis is used to confirm the results. Manufacturers may use these results to strategically select Industry 4.0 innovations which complement their production for improved sustainability.

2. Mass production characteristics

2.1 Economics

Mass production during the Industrial Revolution brought highly automated factories capable of producing large quantities of products. Cost was reduced, but this type of production required a high degree of standardisation. Consumers had to be willing to purchase the same product – for viability, mass production requires mass consumption. Products and the demand for products was not synchronised and consumers had little influence on changes to design. Mass production in the original Fordist sense has largely been replaced by leaner and more flexible systems.

Mass production is both capital intensive and energy intensive. Mass production is based on economies of scale so that capitalization (using financing to purchase equipment which will increase capacity) is almost always the more profitable approach. Equipment is usually the largest fixed cost asset. The goal is to reduce overheads in the cost of production.

Mass production systems are difficult to restructure and lack mobility to respond to changes in consumer demand. Classical material requirements planning (MRP) based production is a 'push' system that schedules the jobs in advance for work centres that push the completed jobs to succeeding work centres. Work in progress (WIP) queues and stock levels may be high and long delays often occur as this approach does not take into account the workload of the next work centre. This may be contrasted with just in time (JIT) which uses a 'pull' approach in which the next job is requested from the preceding work centre only when work is finished so that queues and WIP are greatly eliminated. Elements of JIT and MRP may be combined as 'mixed' systems.

Process manufacturing in industries such as chemicals and petrochemicals, gas processing, power generation or water and wastewater [9] uses two basic types of production: continuous and batch [10]. Discrete manufacturing produces distinct items such as units of piece goods, fluids and pasty products or bulk materials which are processed and packaged. The two basic types of production in discrete manufacturing are continuous and intermittent.

Process industries are usually large-scale operations with general purpose equipment, high levels of automation and system complexity, low speed processes and high product value. Discrete processing is small- to medium-scale with dedicated machines, medium to high levels of automation and low system complexity, very high-speed processes and low product value.

The items of significant cost involved in resource consumption in automated manufacturing systems are: machines and cutting tool holders, computer systems, robot and automated guided vehicles (AGV) systems, automated storage and retrieval systems (AS/RS), fixed assets, externally provided resources, direct and indirect labour, insurance and indirect material, cutting tools and fixtures, direct energy consumption, direct material, and other services such as maintenance, process planning, industrial engineering activities, accounting and finance, administration, and marketing [11]. Where the manufacturing environment is relatively unreliable due to equipment failure, interruptions in work feeding, missing cutting tools, operator absence, etc., push systems may provide better lead time and throughput time performance [11].

2.2 Workforce

At the beginning of the twentieth century, Frederick W. Taylor introduced scientific management to measure the output of workers [12]. The main goal of scientific management was to improve economic efficiency, particularly labour productivity. Monotony of labour may lead to high staff turnover. Taylor's work focused on the needs of the process as opposed to individual worker's needs which led to worker unrest, turnover and social conflict. In modern industry, analysis methods based on Rasmussen's abstraction hierarchy [13] may be used for work domain analysis to support operators.

There are fewer manufacturing jobs in post-industrial economies. Health and safety as well as quality are important considerations in modern manufacturing. In process industries the focus on safety is very high and severe accidents are rare whereas in discrete processing most faults and abnormal situations have only economic consequences and stoppages occur regularly. As a consequence of the different characteristics of the technical systems of process and discrete manufacturing, there are different demands on operators [14]. For example, discrete processing does not require highly educated operators, utilises migrant or seasonal workers with few permanent positions, and tasks are highly repetitive. Repetitive strain injury (RSI) is a common and serious health problem. In contrast, process manufacturing relies on operators with vocational training having an understanding of the process so that proactive measures may be applied to complex interactions in dealing with faults.

Workers in mass production are motivated to focus on functional performance to ensure reliability and efficiency. This may be evaluated quantifiably using measures such as scrap rates [15].

2.3 Environment

Mass production utilises less resources than mass customization, but may contribute to greater waste as consumer needs may not be completely satisfied. The consumers are generally anonymous and hence it is not possible to track products for recycling or remanufacture. End-of-life (EOL) strategies for products that are recovered are likely to be easier to apply due to the uniformity of the products.

3. Mass customization characteristics

3.1 Economics

Customization differs from personalization. Personalization is the identification of a product by the manufacturer based on consumer profile so that it is likely to be unique. Customization involves consumers selecting from a given set of product options so uniqueness is unlikely.

Mass customization aims to produce customised products for individual needs with mass production efficiency. To be successful, manufacturers of mass customised products need to be flexible and quick in responding to market conditions. Although mass customization provides more choice than mass production, the manufacturer retains control over what is produced in contrast to mass imagineering [16].

The 'pull' system drives mass customization. Digital infrastructures may facilitate co-creation via platforms and/or participation in events [17]. However, mass customization faces the challenges of overcoming the convenience of mass-produced products [18], avoiding consumer confusion and overload from overwhelming choice [19], and individuals not confident about their creative abilities. It may not be a viable business model for all industries [20].

Mass customization requires different control systems for manufacturing operations than mass production. Such control systems need to cope with large varieties, very small batch size, random arrival of orders and spread due dates. Usually, the number of variants is predetermined; benefits in increased efficiency and reduced lead times may be related to the further downstream the customization order point is in the value chain [21, 22].

Flexible production technology, e-commerce and information communication technology enable easier customization at lower cost. Flexible logistics and distribution systems are also required. Close proximity to a supplier network of raw materials is important [23]. Information dissemination encompassing operations flows and customer knowledge may be the most important factor in implementing mass customization [24].

3.2 Workforce

Technology and operational systems may facilitate certain customization, but workforce characteristics are important to the development of strategic capabilities [25].

Workers must not only be proficient in their own jobs, but they should be able to integrate and coordinate across functions. In addition, multiple capabilities may be required of manufacturing resources (workers, robots, machines, workstations, etc.) [21].

Depending on the tasks, workers may still develop RSI, but the cause may be more difficult to identify. Similarly, it will be more difficult to establish correlation for other production related effects on health such as exposure to hazardous substances due to task and equipment variety.

Motivation is important so that employees engage in desirable behaviours [26] such as knowledge exchange and combination (KEC) [27] and positive emotions regarding customers [28]. Workers need to perform reliably as in mass production, but also cooperate with external functions to ensure compatibility of components and their integration [29]. Depending on the level of customization, being flexible, proactive and learning-oriented may also be required [25].

Consistent with total quality management (TQM), workers should have autonomy to make decisions regarding their tasks [30]. Task empowerment provides job enrichment and improves motivation and retention [29].

3.3 Environment

Mass customization may benefit from reduced returns and reduced inventory over mass production as more consumer desires are satisfied. Mass customization may be realised in any of the production process steps including design, fabrication, assembly or distribution [31].

Both mass production and mass customization may be modular, but modularity is a key enabler of efficient mass customization [4]. However, it is likely that more material resources will be necessary to make mass customised products compared to mass produced products since it is not possible to optimise modular products with regards to weight and thereby material usage [32].

Mass customization requires greater process flexibility compared to mass production due to greater product variety and subsequent process variety [33]. These different manufacturing processes compared to uniform production are consequently difficult to optimise with respect to energy and material consumption. On the product level, mass customised products may not be as easy to optimise for energy consumption as mass produced products. On the other hand, companies may invest in modules standardised across multiple products to potentially achieve greater energy efficiency than mass produced products.

Mass customised products are likely to be traceable back to a specific customer. This would make it easier to locate products at their end of life. However, end of life mass customised products may not fit another consumer's requirements, making them more difficult to reuse in original form unless the product is designed to be re-configurable or re-personalised [34].

It may be more difficult to determine if mass customised products, or which of their components, have negative environmental or health consequences. This may delay product recalls and other actions aimed at mitigation. An example is e-cigarette devices wherein the characteristics of the heating coils and atomizer may be customised by the users, each component may affect health outcomes independently, and components may interact to create effects different from the sum of their individual parts [35].

If a customised product is not suitable for reuse, the next consideration is to service or repair it. Custom fabricated components may not make it possible to remanufacture products. The variety of parts in a customised product may make it more difficult to service or replace them. A custom fabricated component is likely to be more expensive to replace than using standard components in a customised product. If the mass customised product is not self-reconfiguring and does not contain custom fabricated components, remanufacturing is a good EOL strategy.

The modularity of customised products would likely make them more amenable to upgrading than mass-produced products that do not have this modularity. Modularity would also assist with remanufacturing and recycling. Modular mass customised products may be easier to disassemble than mass produced products that are not modular. Modular product architecture may improve recyclability if it is possible to concentrate material fractions by module.

If a modular design is standardised across multiple products, considerations of material usage and end of life are likely to be issues of concern. If a modular design is assumed but cannot be standardised across multiple products, the most pressing environmental consideration for the manufacturer of mass customised products is likely to be process efficiency.

4. Direct digital manufacturing characteristics

4.1 Economics

Direct digital manufacturing (DDM) is the interconnection of decentralised additive manufacturing equipment and modern information and communication technology (ICT) [7]. DDM combines product design with manufacturing technology, usually 3D printing or additive manufacturing, to directly convert digital models into physical objects without the need for tooling. DDM uses 3D (CAD) models for direct fabrication of products without the need for process planning [36].

The use of DDM as a broad umbrella term encompasses applications in prototyping, tooling, low-volume parts manufacturing and customised product manufacture. Distributed production is a likely outcome of the use of DDM [37] with the expected emergence of agile supply chains [38]. The technology enables the matching of consumer demand and supply capacities in real-time, limited only by physical logistics.

Product characteristics for additive manufacturing are customisation, increased functionality through design optimisation and low volume. Investment in additive manufacturing may be seen as a structural investment which builds new manufacturing capabilities [39].

It is important to distinguish between personal fabrication and social manufacturing [40]. Personal fabrication is when individuals make products for their personal use employing, for example, home 3D printers. Social manufacturing occurs when individuals cooperate with organisations as part of production.

Industrial 3D printers cost around £20,000, but low-cost 3D printers, some of which are self-replicating, are available to the public [41] for about £500. One of the top-rated 3D printers currently on the market sells for about £2600. Some home 3D printers have the capability to print three different materials in one session for 3D prints that have moving parts.

The key perceived strengths of additive manufacturing are agility, in-process visualisation, novel business models, reduced upfront fixed cost and risk, potential for decentralised production, and a reduction in transports [42]. DDM has the potential to dramatically change conventional supply chains if the 'factory in every home that can make more factories' is achieved [41]. The only transport related to home use of products printed at home would be of the raw materials, usually in the form of wire or powder. Cost analysis indicates home manufacturing is a profitable proposition for U.S. households [43, 44].

Prices and times to print large objects increase exponentially. Even though 3D printed health aids are becoming available, regulating the conformity and quality of products in general is problematic [45]. Other technical challenges include time-consuming 3D object design, limited types of usable materials, low precision and productivity [46]. Additional labour costs may be incurred for post processing such as removing residual powder – this is often underestimated or neglected [47].

It has been demonstrated that 3D printing may be applied to mass production/mass customization [46, 48, 49]. The advantages of 3D printing over conventional mass production methods include saving time, money and effort in creating the dedicated capacity and materials, prototyping and moulding. A quicker response may be achieved by using multiple 3D printing facilities simultaneously in a local area using industrial Internet of Things (IIoT) technology and maximising the closeness to JIT [8].

Mass imagineering digital infrastructures may require a high level of technology awareness. Internet-enabled global networking may provide the means for financial rewards at almost no financial risk, but time may need to be invested. There may, however, be risks to personal reputation [50].

Research has found that the key driver for adoption of additive manufacturing is the capability of producing almost any complex design with economic motives being pivotal [51].

4.2 Workforce

The toxicological and environmental hazards of handling, using and disposing of materials used in DDM processes are not fully understood. Compared to processes such as casting, forging and machining, workers do not experience long-term exposure to noise and oil mist from metal working [52]. However, 3D printing is being associated with the release of volatile and very volatile organic chemicals and billions of airborne particles per minute with potential for inhalation and consequent health risks [53, 54]. Although many industrial 3D printers are enclosed, workers may still be exposed to inhalation risks when retrieving the printed parts. Occupational exposure limits have yet to be established for 3D printer emissions [55]. As with any new technology, these issues should be resolved over time.

The premise behind DDM is that designs will be co-created through collaboration. Acquiring the necessary skills may be possible online using basic knowledge of computers. This may enable promises of equality, justice and self-actualization. But this may also lead to the exploitation of individuals who may or may not realise that digital infrastructures are collecting their personal data and that they are doing unpaid work [56, 57]. Work that is paid may be poorly paid, precarious and intermittent. For profitable mass production using DDM, design is likely to be key and the extent to which co-created designs may outperform those of traditional mass production or mass customization remains to be seen.

Furthermore, there is no absolute geometric freedom and many considerations for eco-design which existing methods and guidelines for conventional manufacturing do not cover indicate that to realise the full potential of DDM for more complex products, specialist designers may be required [58]. Design for do-it-yourself is under-explored in academia [59].

4.3 Environment

Very little sustainability research has examined personal fabrication, social manufacturing or even the industrial use of DDM in distributed production [37]. The environmental implications of these evolving manufacturing processes have not been extensively examined [47]. The focus of research has been on sustainable development through additive manufacturing by (1) improved resource efficiency permitted by redesign of both products and processes for in-house waste minimisation; (2) product life extension using technical approaches and stronger person-product relation; and (3) simplified value chains by reduction of logistic complexity and placing production nearer to the consumer [60].

Environmental effects such as biodegradability and ecotoxicity are not fully understood. Similarly, little is known about the chemical solvents used for removing excess material during the steriolitography (SLA) process as well as environmental effects related to selective laser sintering (SLS), laser additive manufacturing (LAM), dynamic magnetic compression (DMC) and direct metal fabrication (DMF) [61].

Evaluation of the energy consumption has not been thoroughly investigated [51] nor has water consumption and treatment [61]. Polymers, the most processed type of powders in SLS, have quite a low sintering temperature (<200°C). A partial consideration of SLS which does not include the efficiency of the laser source or auxiliary energy finds a low energetic intensity of the process, but there is no direct comparison possible with other rapid prototyping techniques or conventional manufacturing processes from the quality perspective [62]. Smaller thickness layer and optimal part orientation may overcome surface quality issues, but processing time and thus energy consumption is increased [58].

Additive as opposed to subtractive manufacturing may help to reduce material input into production. Not all material from DDM is reclaimable. Powder bed processing of polymers causes up to 50% of the build volume in waste which cannot be reused. Significant energy may be required in the production of the required raw materials (feedstock), but there may be significant saving if recycling is possible [47]. There is potential to combine surplus agricultural materials such as soybean to create composites of comparable strength to those made from petroleum-based resins [63] or to utilise local waste streams (mussel shells) [64].

Energy savings may be obtained through reduced material demand and use phase savings due to lighter weight. However, the benefits of components produced through additive manufacturing versus traditional manufacturing are questionable for automotive components when considered in the context of additional manufacturing impacts caused by powder production, processing and post treatment [65]. Some authors have concluded that it is not possible to determine whether 3D printing is more environmentally friendly that machining or vice versa [66].

It is likely that hybrid additive manufacturing and subtractive manufacturing will be desirable so there will be a need for intelligent algorithms to determine process parameter combinations. With multiple additive manufacturing systems, an intelligent factory with resource allocation and self-organisation capabilities would be optimal [58]. An investigation of DDM-based operational practices to build sustainability capabilities anticipates increased local supply chain partners, reduced material flows, inventory and transport operations, and more sustainable product lifecycle management [67]. However, many of these operations are likely to be complex such as the addition of sensors to products, the extent of customer control over the production process and dynamic supply chain reconfiguration.

Distributed manufacturing may significantly reduce transports over centralised manufacturing [68], however, raw material transport may offset some of these benefits. There is a significant risk that additive manufacturing may trigger a rebound effect through an increase in overall consumption, especially in fashion products [69]. It is also not clear whether mass customization in DDM will precisely match consumer needs and thus eliminate waste, or if the availability of DDM will increase waste through trial productions. Environmental sustainability benefits are barely relevant to the decision of manufacturers to adopt additive manufacturing which contrasts with literature stating the considerable sustainability benefits [51].

The eco-design concept enabled by additive manufacturing has the most potential for providing sustainability improvements [58]. Symbiotic, life cycle and closed loop links could significantly reduce or eliminate the negative impacts of additive manufacturing. Improved design has the potential to increase market acceptance which may lead to reduced waste. Additive manufacturing has potential to provide spare parts and impact the modularity of products relevant to circular economy efforts [70]. As additive manufacturing may be used to repair or remanufacture damaged components, savings of up to 50% may be achieved [47]. More efficient designs may be possible with additive manufacturing as well as the integration of additional technical functionality [47].

5. Smart production innovations

Cyber-physical systems (CPS) facilitate the connection and communication of software and mechanical or electrical elements using wired or wireless data infrastructure. This technology makes it possible to monitor and direct production systems with complex processes at all hierarchy levels and with high product varieties. The anticipated paradigm shift in manufacturing to Industry 4.0 or smart factories and production systems will decentralise traditional centralised applications for production control [71]. Industry 4.0 innovations/technical developments which will enable this paradigm shift include [72]:

1. Cobots that will assist workers in handling physical objects.

2. M2M meaning machines will communicate with each other to improve process flow, do capacity planning and reduce process time. This will include the monitoring of components for wear to prevent or reduce breakdowns.

3. RFID and NFC technology enable wireless communication. This technology is currently used in warehouse management and logistics, product tracking in supply chains, product security, raw material tracking, point of sale, and other applications.

4. QR codes used to identify parts or tools, or provide more information about a product.

5. Augmented reality to display additional information such as instructions, or to help with visualisation of objects in a physical space. Simulation may enable quality control so that potential defects may be corrected prior to physical production.

6. Mobile devices that may be used to give instructions to workers, apps may monitor or control machines, machines may be tracked via QR codes, and images or videos may be sent as part of support or service.

7. Condition monitoring/predictive maintenance reduces unscheduled machine stoppages using electric motors to measure and track data about mechanical stress and operating temperature which are usually sent to a cloud for storage and analysis. This reduces waste as parts are replaced after they are worn as opposed to after a pre-defined life.

8. Production based on the pull principle means that raw material or semi-finished production material is requested on demand automatically. Technology may be used to enable hybrid push-pull manufacturing based on customer order decoupling point (COPD) [73].

9. Intelligent resource management connecting machines and power plants can plan energy intensive activities when surplus energy is available.

10. Localised sourcing of parts has the benefit of providing local employment and reducing transports.

The effect of Industry 4.0 on sustainability is unknown in detail. Smart production systems are expected to reduce waste, overproduction and energy consumption. The following section will introduce the sustainability hierarchies and apply them to mass production, mass consumption and DDM to determine which of the above Industry 4.0 innovations would be of greatest benefit with respect to the financial, environmental and social sustainability needs of manufacturers.

6. Hierarchies of sustainability dimensions

Needs-based hierarchies for the sustainability dimensions reflecting the triple bottom line [74] are shown in **Figure 1** below [75].

Environmental impact has been used to justify the hierarchy of end-of-life strategies [76]. The sustainability needs hierarchies in **Figure 1** reflect the current sustainability discursive paradigm with respect to impact on the manufacturer.

The financial and social hierarchies may be considered in terms of time to failure if sufficient capability is not achieved, e.g. if a critical machine (tangible asset) fails, products cannot be made until it is repaired and business will be lost when current inventory is exhausted. The application of the environmental hierarchy is more complicated as the impacts are cumulative, e.g. reducing the amount of material input improves process efficiency and is likely to reduce waste.

The hierarchies connect to systems at higher levels and treat each dimension of sustainability individually unlike the general Corporate Social Responsibility (CSR) need-hierarchy [77]. The hierarchies also reflect the current view that sustainability is no longer considered at the self-actualization level of needs, but rather the necessary reorientation of manufacturers from profit toward the holistic well-being of all stakeholders so that sustainability is a consideration at all levels. It is important to note that needs at the lower levels should be satisfied to maximise impact, but as with Maslow's hierarchy of needs, it is possible to pursue needs at higher levels simultaneously.

A distance-to-target methodology may be used to determine indicators within the hierarchies as the sustainability impacts do not need to be converted to a unified form such as money, energy or ecological footprints [78]. An example of targets and their impact on the manufacturer if targets are not met corresponding to **Figure 1** is shown in **Table 1**.

The examples of **Table 1** indicate that the sustainability needs hierarchies arise primarily from a strategy perspective similar to the hierarchy of corporate resources [79].

6.1 Extension of the hierarchies to mass production, mass customization and DDM

The hierarchies may be applied to cases of individual manufacturers [75] or, more generally, to a method of production. Based on the preceding literature

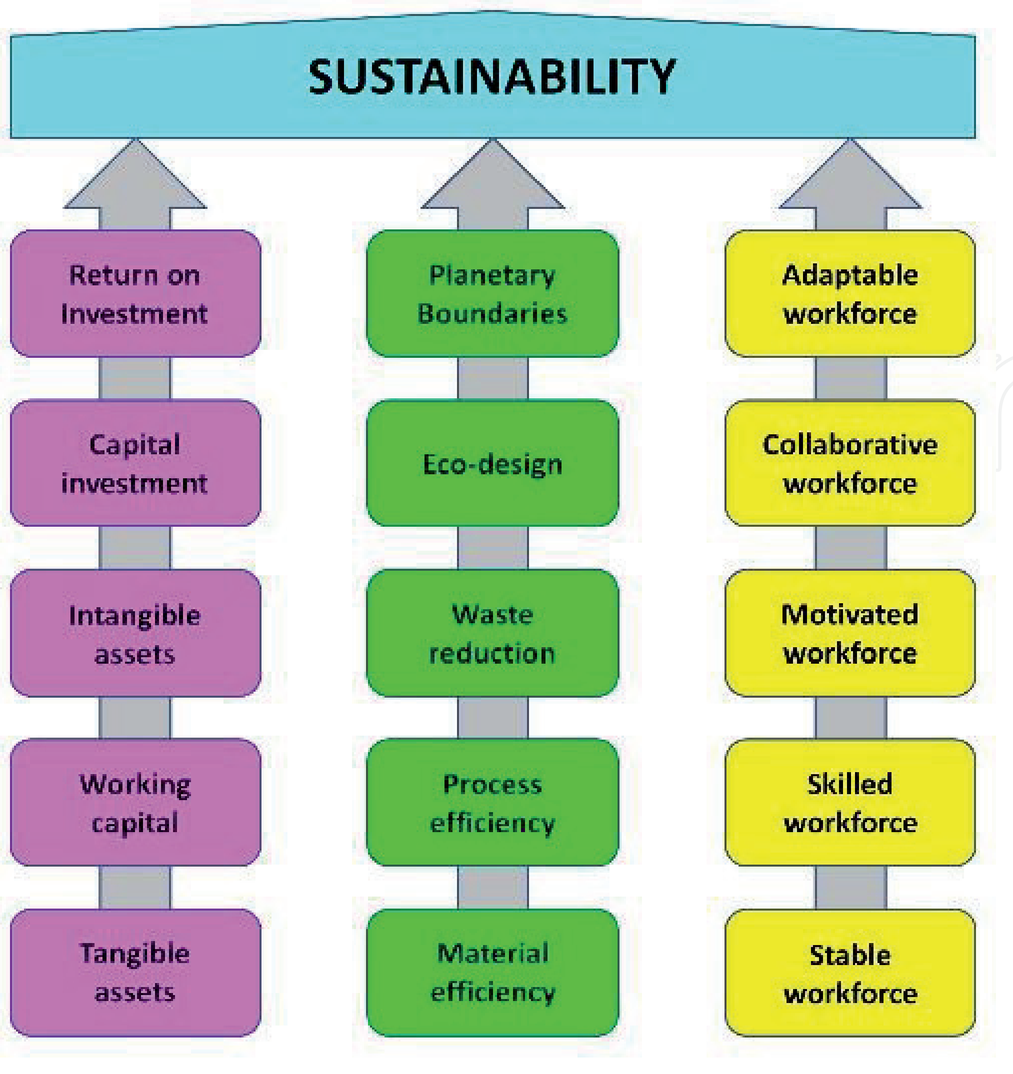

Figure 1.
Sustainability needs hierarchies for manufacturers [75].

Financial needs		**Environmental needs**		**Social needs**	
Target	**Impact if not met**	**Target**	**Impact if not met**	**Target**	**Impact if not met**
Dividend payments	Loss of investor interest	Emissions within limits for planetary boundaries	Unsustainable planet	Innovation (patents, IP)	Industry stagnation
No obsolescence	Years based on depreciation time to loss of competitive-ness	All products and processes co-designed for environment	Climate change, severe weather events, etc.	Customer satisfaction	Loss of customers
No brand failure	Months to loss of customers	Zero waste	Pollution, contaminates, etc.	Optimal production output	Suboptimal production performance
Adequate working capital	30–60 days to loss of production capability	Reduced energy consumption	Decreased time to fossil fuel unavailability	No health and safety issues	Decreased effectiveness of production
No unscheduled stoppages due to breakdowns	Immediate loss of production capability	Reduction of raw material input into production	Decreased time to critical material shortages	No unscheduled stoppages due to workforce instability	No production

Table 1.
Examples of targets and their related impacts.

Method of production		Financial needs hierarchy	Environmental needs hierarchy	Social needs hierarchy
Mass production	Discrete	Tangible assets	Waste	Stable workforce
	Process	Tangible assets	Waste	Skilled workforce
Mass customization	Modularity Across products	Intangible assets	Resource efficiency	Collaborative workforce
	No modularity across products	Intangible assets	Material efficiency	Collaborative workforce
Direct digital manufacturing (DDM)	Household	Return on investment (ROI)	Eco-design	Adaptable workforce
	Corporate	Working capital	Eco-design	Adaptable workforce

Table 2.
Hierarchy levels for mass production, mass customization and DDM.

Method of production	Industry 4.0 innovation/technical development		
	Financial need	**Environmental need**	**Social need**
Mass production	Condition monitoring/ predictive maintenance	Production based on a pull principle	Cobots (discrete)/ augmented reality (process)
Mass customization	RFID, NFC technology/QR codes	M2M (resource efficiency)	Mobile devices
Direct digital manufacturing (DDM)	Intelligent resource management connecting machine and plant for mass DDM (corporate)	Augmented reality	Localised sourcing of material

Table 3.
Matching industry 4.0 innovations to methods of production.

review of mass production, mass customization and DDM, **Table 2** indicates the corresponding level of most impact for each of these production systems in the hierarchies.

6.2 Integrating manufacturer needs with industry 4.0 innovations

Using **Table 2** of the needs with the most impact on the method of production, it is now possible to use the descriptions of the Industry 4.0 innovations and match them to these needs to indicate where the greatest sustainability benefit may be achieved. The result is shown in **Table 3**.

7. Value analysis

The sustainable value analysis tool (SVAT) [80] is applied to each of the production systems to confirm the results of the hierarchies. The purpose of SVAT is to analyse multiple forms of value across the entire life cycle through the dimensions of economic, social and environmental sustainability. SVAT may be implemented in four steps:

1. Product life cycle definition;

2. Description of value captured;

3. Identification of value uncaptured; and

4. Analysis of value uncaptured and exploration of value opportunities.

For the first step, a modular product is assumed. At the beginning of life, this modular product may be mass produced, mass customised or be the output of DDM in a business context. The use phase at the middle of life is assumed to be the same for all production processes. The modular product is also assumed to be fit for disassembly into modules for end of life treatment such as remanufacture, refurbishment or recycling.

Tables 4–6 describe value captured and value uncaptured for each production system based on the literature.

The value opportunity for each production system may be associated with an Industry 4.0 innovation. Value opportunities are identified through new activities and relationships. Each identified value uncaptured may be analysed to find its source. Reducing value uncaptured through potential solutions leads to value opportunities.

The value opportunities for mass production include incorporating 'pull' into the production system, finding an activity or relationship to utilise overproduction, entering into relationships to better enable product recovery as well as improving

Mass production		**Beginning of life (BOL)**	**Middle of life (MOL)**	**End of life (EOL)**
Value captured		Economies of scale, standard product and process design	Economies of scale for distribution and retail, standard service and maintenance	Uniform treatment
Value uncaptured	Value destroyed	Large throughput leading to more pollution	Unsatisfied needs leading to waste	Increased capacity required due to waste from MOL
	Value missed	Push production, inflexible product and process design	Understanding of consumer, product use data	Information about product location
	Value surplus	Overproduction	Potential satisfaction of a large number of consumers	Product availability in large quantities
	Value absence	Labour shortages, stoppages and breakdowns, high risk in tangible asset investment	Lack of customization/ personalization	Product recovery not enabled – reliance on third parties

Table 4.
SVAT analysis for mass production.

Mass customization		**Beginning of life (BOL)**	**Middle of life (MOL)**	**End of life (EOL)**
Value captured		Pull production, flexible production, minimal inventory	Greater need satisfaction	Product and consumer data
Value uncaptured	Value destroyed	Input resource inefficiencies, changeovers and process inefficiencies, more packaging	Increased transport for distribution, more complex service and maintenance	Complicated product treatment
	Value missed	Complicated product and process design	Product distribution combined with other distribution or collection	Product collection combined with other collection or distribution
	Value surplus	Workforce capabilities	Consumer use data	Product location for recovery
	Value absence	Lack of economy of scale in production	Lack of economy of scale in distribution and retail	Lack of uniformity in product treatment

Table 5.
SVAT analysis for mass customization.

Direct digital manufacturing (DDM)		**Beginning of life (BOL)**	**Middle of life (MOL)**	**End of life (EOL)**
Value captured		Personalization of product, niche applications, no tooling or process planning, localised sourcing of materials, minimal inventory	Distributed production, need satisfaction	Spare part production
Value uncaptured	Value destroyed	Waste, resource and process inefficiencies	Traditional retail and distribution, potentially complicated service and maintenance	Landfill
	Value missed	Need for new supply chains, limited material options, expensive input material, resource and process inefficiencies, slow production, small batches, quality issues	Increased transports	Complicated collection and treatment
	Value surplus	Potential overcapacity of free/cheap labour to exploit	Potential excess capture of personal data	Potential excess of material available for reprocessing
	Value absence	Lack of competent designers, health risks	Lack of facilities for maintenance and service	Lack of suitability for treatment

Table 6.
SVAT analysis for DDM.

product design to reduce use phase impacts. Reducing labour shortages and lower risk related to the high tangible asset investment would also be a target.

The value opportunities for mass customization include improving resource efficiency, entering into relationships to fully utilise product distribution and collection, and the provision of suitable information to those engaged in end of life treatment of products.

The value opportunities for DDM centre on relationships with designers for improvements at all life cycle stages. New relationships should be developed for both supply chain and reverse logistics.

8. Conclusion

The main contribution of this chapter is the assessment of smart production innovations related to Industry 4.0 to determine the most beneficial for mass production, mass customization and direct digital manufacturing, respectively, taking into consideration the three dimensions of sustainability (**Table 3**).

SVAT yields the same conclusions, although less refined, as the manufacturer needs hierarchies in respect of Industry 4.0 innovation selection.

Manufacturers should consider their strategic sustainability needs based on their production system when selecting smart production innovations.

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