

Review

Towards the Development of a Digital Twin for a Sustainable Mass Customization 4.0 Environment: A Literature Review of Relevant Concepts

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Abstract: Digital Twins (DTs) are one of the disruptive technologies associated with the Industry 4.0 concept. A DT connects the physical manufacturing system with the digital cyberspace, via the synchronization of the simulation (i.e., physical configurations) and data models (i.e., product, process, and resource models) of the manufacturing system. This synchronization of both worlds—the physical and digital—allows one to address the issue of manufacturing customized products. This challenge of mass customization (1) puts forward the goal of achieving the highest level of customer satisfaction, and (2) creates the need for the optimization of the complete value creation process. Within an Industry 4.0 context, the latter is translated as the interlinking of production resources and systems, via a DT, as it is in the physical world where the actual value-creation process takes place. The success of an Industry 4.0 mass customization environment (or mass customization 4.0), depends on its degree/level of sustainability. For these reasons, the present paper presents a review of relevant concepts related to the role of DTs in the achievement of a mass customization 4.0 environment, plus some proposals of how to address the identified research challenges. A future research agenda is proposed at the end of the paper.



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1. Introduction

In today's global competitive market, manufacturing companies are facing the challenge of moving from mass-production to mass customization [1] where meeting individual customer expectations and achieving the highest level of customer satisfaction requires one to rapidly deploy businesses interactions [2]. This presents companies with a series of business challenges, such as manufacturing a high variety of high quality, high performance, low cost, smart, highly customized/individualized products [3]. Being part of a mass customization market implies giving the customer the opportunity to be part of the value creation process [4] through the design and definition of their own individual products and/or services [5] by combining functions and components [6] and producing them in small lot sizes, ideally, a batch size of one [7,8] with quick delivery requirements [9,10] and without paying a high price premium, that is, maintaining the economic conditions of mass production [11,12].

The challenge of mass customization puts forward a value proposition of achieving the highest level of customer satisfaction [4], which creates the need for the optimization of the complete value creation process [13]. This in turn requires grouping together different value creation functions [14–16] and the development of new value creation mechanisms [17]. Now, in order to manage this whole value-chain (in an agile and responsive manner), virtual and physical structures are needed [18], and these must be supported by the intensive use of automation, computer systems and software [19]. These issues can be related directly to the Industry 4.0 concept, a very popular initiative among manufacturing companies [20], as

manufacturing systems are forced towards an increased level of adaptability and flexibility in order to reduce the time-to-market [1].

1.1. Industry 4.0 and Mass Customization

Industry 4.0 combines technologies such as the Internet of Things (IoT), Big Data, and cyber-physical systems (CPS), Digital Twin (DT), etc., in order to integrate the industrial value creation process chains [21,22] via the real time availability/sharing of relevant information between humans and machines [23–25], something that has big implications for sustainability [26]. More specifically, the main tasks of these Industry 4.0 core technologies are digitization of data, analysis, and knowledge extraction [27], that can be used:

- To enforce automation flexibility [28];
- To increase the level of manufacturing efficiency [29], flexibility [30], and competitiveness/productivity [31];
- To integrate all the value-adding chain [31].

Now, a great variety of studies show that the Industry 4.0 concept has the potential for meeting affordable/economic mass customization [8,9], as there is a need to use reconfigurable, adaptive, and smart manufacturing, evolving-factories [32]. According to [20], Industry 4.0 is regarded to be the response to the mass customization challenges, as it requires the use of innovative technological production approaches [33], while [34] states that one of the goals of Industry 4.0, when implemented to address the challenges of a mass customization market, is to successfully achieve a high level of sustainability. This supports the idea that the implementation of the Industry 4.0 concept should take the needs of mass customization into account [35]. Within this general context, the optimization of the value creation process chain (understood as the rapid service-oriented response to the mass customization market demands/requirements), needs to be addressed through the use of fully automated and digitalized processes [36], while at the same time considering the environmental and social impacts that guarantee durable competitiveness [37]. This in turn imposes some challenges:

1. The need for the development of entirely new business models [38] and their associated business processes. According to [39], a business model focuses on the “what” side of value creation, while a business process model focuses on the “how” side of value creation. As customers are integrated into the value creation process by defining and configuring individual solutions a tool is needed to accomplish this [40]. In the age of Industry 4.0, this refers to:
 - A real-time, up-to-date information flow model, that allows the elimination of business process delays [41], through the rapid identification of customer needs and the simplification of the customization process [42];
 - The digital networking of production processes and resources [43,44], to systematically record/process data, in order to support a transparent and responsive supporting system.
2. The support of a manufacturing environment should be suitable to be scalable at no extra cost [45–47]. This scalability refers to the production system reconfiguration that takes place through the integration of plug-and-produce, fully automated, digitized, highly cost efficient, smart new manufacturing units [7]. This calls for the use of new efficient re-configurable manufacturing methods such as the CPS [48], where its real time, production coordination capabilities allows boosting customer satisfaction by economically producing customized products [49,50]. These coordination capabilities come from the efficient processing of a vast amount of information (coming from tightly connected sensors, controllers, manufacturing systems, etc.), that later on is transformed into optimized decisions [51].

1.2. Digital Twins

A Digital Twin (DT) is a structure of inter-connected digital replicas of physical entities [52,53] plus their related meta-information and semantics [54], that enables real-time interaction and integration [55] between the physical and digital worlds [56], i.e., physical manufacturing system and the digital cyberspace [2,57,58]. This translates in an intensive bi-directional [59,60], standardized and/or automatized [61], real-time information flow [35] related to the current products, processes and resources [62] between the DT and the real manufacturing system [63,64], via the internet [65]. A more formal definition of DT manufacturing is provided by [66]: “... DT is a virtual representation of the physical configurations and the dynamic modeling of product, process, and resource changes during manufacturing...”. In [67], the authors present a well-founded review of the types and applications of digital twins; ref [66] presents a detailed characterization of a digital twin for production systems; refs [68,69] present an application of digital twins in production systems. DTs have an impact/influence in several other areas:

- Industry 4.0: a DT requires a set of technologies needed for its implementation including, but not limited to, simulation methods, communication protocols, and the core technologies of Industry 4.0 [60], a concept that has emerged as a manufacturing enabler to achieve the desired time-to-market reduction [70];
- Mass customization: the demand for highly individualized products with shorter lifestyles drives modern manufacturing systems to focus on the use of information technology-based manufacturing systems [71], such as the so-called data-driven Digital Twins [58]. A DT of a manufacturing system in the form of a simulation and data model [61] that synchronizes both the physical and digital worlds [72] can be used to address the issue of manufacturing customized products [2], as it makes the deployment of the required flexible and reconfigurable manufacturing system possible [73];
- Manufacturing efficiency: the added value of a DT is the quick assessment and analysis of reconfiguration changes [74], improved efficiency [31,59], and performance prediction [56], of its manufacturing system counterpart [75];
- Sustainability: DTs may be utilized to address these sustainability challenges [10]. For example, social sustainability requires the integration of human skills with technology [76], and the improvement of the environmental and social factors of smart manufacturing may conflict with the economic factor [35]. In [77] the authors depict a sustainable digital twin (SDT) framework for shifting from a static sustainability assessment to a digital twin (DT)-based and Internet of Things (IoT)-enabled dynamic approach;
- Value Creation: within the DT context, the importance of the physical world resides in the fact that it is there where the actual value-creation process takes place [66].

A recent study presented by [78] distinguishes the concept of a DT with that of a Digital Shadow (DS). According to this author, the main difference can be stated in the following way: if a virtual model represents the physical model only, with one-way data flow, this is considered to be a Digital Shadow (DS); in a DT, both the virtual and physical entities communicate with each other. The author concludes that when developing a DT, sustainable development goals should be considered as well, in addition to the technical ones. On the other hand, a recent paper by [79] presents a systematic literature review of ninety-eight research papers dealing with the various dimensions of a DT developed at a supply chain level, giving special emphasis to the achievement of sustainable performance objectives. The results of this study reveal that such DT should follow a socio-technical holistic approach and should not be restricted to the local manufacturing systems domain. For that matter, the author presents a sustainable DT framework for supply chain systems. Among the many implications derived from this framework is the contribution to value capture, one of Industry 4.0 value domains, in the form of monetization strategies for products and services.

1.3. Digital Twins and Small and Medium-Sized Enterprises

The application of Industry 4.0 technologies presents two fundamental issues [80]; on the one hand, the high investments required, and on the other hand, the risks surrounding these types of projects, i.e., uncertain profitability [81]. This is particularly true for small- and medium-sized enterprises (SMEs) looking to transition towards digital transformation [82]. Even though SMEs are the pillar of the economy in many countries due to their contribution to gross domestic product creation [83,84], they have issues when adopting the latest technology [85], in particular the lack of financial resources to face costs in the form of software and expertise [86]. Moreover, when adopting/implementing technologies, such as the so-called Digital Twin (DT), SMEs face some issues, barriers, and limitations [82]; lack of expertise to manage complex Industry 4.0 structures (that is, how to digitalize/extract/visualize data which is valuable and helpful to the business), concerns about data and cyber security, lack of appropriate digital infrastructure, etc. For this reason, SMEs must explicitly perform a cost–benefit analysis (from the very beginning) of their specific circumstance and evaluate whether such costs justify the long-term benefits [86] in order to maximize the chance of success and generate sustainable competitive advantages for organizations [80].

2. Research Gaps

The following section covers the following topics: Industry 4.0, manufacturing efficiency, mass customization, sustainability, and value creation (Table 1 summarizes this review). Based on this analysis, we propose a research agenda to address the identified research gaps.

2.1. Sustainability and Manufacturing Efficiency

The balance between the elements of the triple bottom line (TBL) of sustainability (that is, the economic, environmental, and social elements) is a necessary condition for the continued success of an organization [87]. Sustainability can be understood from the perspective of successful/efficient manufacturing execution, which result from the implementation of technologies associated with Industry 4.0, as the high efficiency smart manufacturing system [88]. According to [89], the efficiency of an organization's operation—that is, the better use of resources by the transformation process [4]—depends on the correct alignment between its strategic and operational levels. A tool developed to aid in the linking/alignment of both the strategic and operational levels is the Customer-Product-Process-Resource (CPPR) framework (Figure 1) proposed by [90–92]. In fact, as this strategic-operational levels linking/alignment affects the performance of a manufacturing organization [93], it becomes necessary to take it into account in order to reach high levels of sustainability (by avoiding poor efficiency in both managerial and transformation processes). On the other hand, according to [94,95], a critical enabler for an efficient mass customization process is the flexibility of the production system, that is the capability to offer product mix and changeover [96], as it allows a fast and easy reconfiguration of production facilities [97]. However, the higher process flexibility is, the more difficult it is to achieve a high manufacturing efficiency, an issue that can be properly addressed by the use of automation [98]. As the mass customization challenge requires the use of more flexible resources [99], from here we will consider the idea of addressing it through the use of an Industry 4.0 environment [100–102], more specifically, the use of a CPS-based smart manufacturing system.

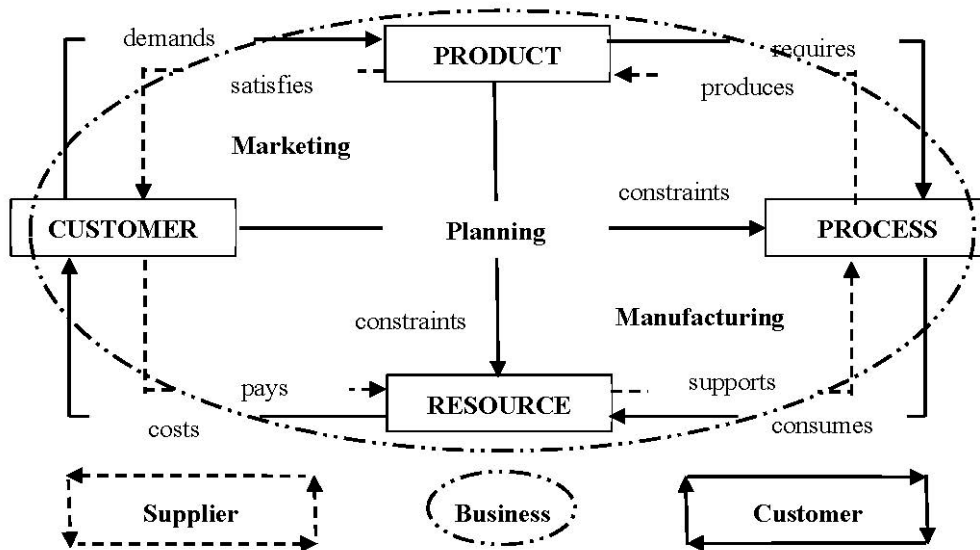


Figure 1. The CPPR framework, based on [91].

2.2. Sustainability and Industry 4.0

Authors such as [103–105] mention that even though the implementation of Industry 4.0 can help in the quest for achieving sustainability, it is not clear how this is done. [106], and [107] agrees with the idea of the sustainability implications (for an organization) from the implementation of the Industry 4.0 concept. For example, a smart manufacturing system, an associated technology to Industry 4.0, is defined as a CPS coupled with (1) a decentralized, self-contained execution and decision-making structure, [108], and (2) a “self-conscious” environment [99]. The use of this technology makes it feasible to achieve the high levels of efficiency needed for a sustainable environment [109–111]. From here we will consider the idea that sustainability is a main requirement of a smart manufacturing systems [112,113], and that the use of this technology can help implement a sustainable production process [114]. Regarding the core technologies of Industry 4.0:

- Studies [115–118] discuss the importance that Big Data Analytics has in supply chain sustainability. Big Data technology has been used for energy consumption monitoring [119] and energy efficiency optimization [120], to achieve sustainable smart manufacturing [121];
- The introduction of IoT technology promotes sustainability in a global context [122,123];
- The combination of Big Data and IoT technologies enables sustainable production processes [117,121];
- Virtual Reality (VR)/Augmented Reality (AR) technologies lead to sustainability via better training and knowledge [124];
- Cloud manufacturing technology improves the efficiency of a manufacturing system [125], reflected as low production costs and high levels of productivity and sustainability [121].

Appendix A presents some complementary material regarding the use of Industry 4.0-related technologies for the assessment of sustainability.

2.3. Sustainability and Value Creation

In [126], the authors consider sustainability to be one of the elements of a business model, while [127] suggests that in fact, business models must guarantee sustainability. Within this context, a business model ontology would make the design of a sustainable business model easier [128]. Regarding the implementation of the Industry 4.0 concept, even though sustainability can be considered one of its business features [129], it only addresses it when there is an economic benefit [4]. In fact, an Industry 4.0 sustainable business model is defined as “how to run a company in a sustainable way” [4], but there is

no qualitative assessment of how Industry 4.0 contributes to sustainable value creation [130]. With the idea of reflecting the value domains of Industry 4.0, [131] developed the CPPR 4.0 framework (Figure 2), based on previous work by the author ([91,92]), plus the inclusion of the work of [130–133], in the area of value creation.

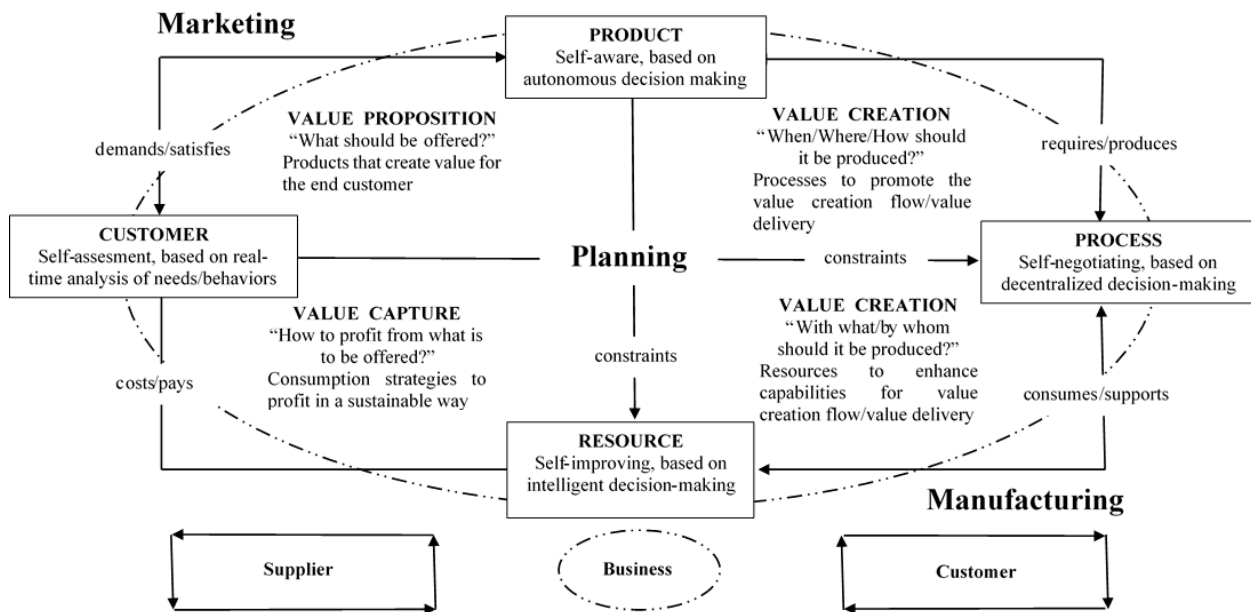


Figure 2. The CPPR 4.0 framework, from [131].

Table 1. Literature review summarizing table.

Sustainability and ...	References
Manufacturing Efficiency	[4,88–93]
Mass Customization and Industry 4.0	[93,96,97,99–102]
Industry 4.0	[103–107]
Smart Manufacturing	[99,108–114]
Virtual/Augmented Reality/Cloud Manufacturing	[115–118,121,124]
Value Creation	[4,126–133]

2.4. Research Features

Digital Twins (DTs) connect the physical manufacturing system with the digital cyberspace. By synchronizing both worlds, the issue of manufacturing customized products can be properly addressed. In turn, this demands one to address the issue of sustainable value creation, especially if this mass customization takes place within an Industry 4.0 context. These ideas are synthesized in the concept of Sustainable Mass Customization 4.0 (SMC4.0), introduced by [134]. In general, SMC4.0 refers to the use of a re-configurable CPS as the basis of a mass customization production system, where the idea is to take advantage of the manufacturing efficiency of the smart manufacturing transformation processes to achieve the desired levels of sustainability. In this case, a transformation process is a chain of sequenced activities that transform inputs into outputs, while adding value in the process and consuming resources in between [135]. Now, in order to truly operationalize the SMC4.0 concept, it is necessary to understand it in terms of both a business and manufacturing environment:

- (1) The SMC4.0 business environment refers to a business model that reflects the economic benefits of achieving sustainability (in a context of manufacturing efficiency), plus the environmental and social impacts that will guarantee durable competitiveness;
- (2) The SMC4.0 manufacturing environment refers to a rapid responsive (quick and profitable), service-oriented (ability to fulfill the demand for highly customized products) manufacturing model.

From the perspective of a DT, this translates into the development of a real-time, up-to-date, information flow model, that assures successful/efficient manufacturing execution via the proper placing/timing of the key resources/activities, and with this, the achievement of sustainability. Thus, as the first step into building a DT with SMC4.0, we propose to use an approach similar to the one followed by [136–138], when building a reference model, where a “best of breed” approach combines and integrates academia initiatives that have never been put together before (which in the words of [139,140], can be considered an original approach). This requires a review of the literature in the areas of (1) sustainable value creation within an Industry 4.0 environment, and (2) the business process behind the mass customization process.

The rest of this document is composed of Section 3, which introduces a set of relationships and abilities required by the sustainable value creation process (the goal of this section is to understand what are the elements behind the process of creating value in a sustainable way); Section 4, which introduces a set of basic information elements related to the sustainable value creation process (the goal of this section is to understand what are the information elements involved in the process of creating value in a sustainable way; and Section 5, which describes the future research efforts that should be taken and offers some final conclusions.

3. Sustainable Value Creation

3.1. The Sustainable CPPR 4.0 Framework

More recently, ref [141] presented a sustainable business model canvas (SBMC) based on the TBL of sustainability (Table 2 summarizes its features). As we are interested in this document, in understanding what are the elements behind the process of creating value in a sustainable way, we claim that Cosenz’s sustainable business model canvas [141] can be used to update the original version of the CPPR 4.0 framework and derive Sustainable CPPR 4.0 (Figure 3). In order to include all the elements of sustainability:

- Each quadrant of the framework presents the questions pertaining to each value domain, i.e., the WHO of value delivery; the WHAT of value proposition; the WHAT/WHEN/WHERE/HOW of value creation; the WHY of value capture;
- The answers to these questions, for each value domain, can be found in Table 2;
- The arrows pointing direction (in Figure 3) indicates the customer (clockwise, solid line) and supplier (counterclockwise, dotted line) standpoint, when reading the framework.

Figure 4 presents the quadrants (of the Sustainable CPPR 4.0) related to the value creation domain, and within those quadrants, the relationships between the elements that define value creation form an economic value perspective (similar relationships can be derived for the environmental and social perspectives).

Table 2. Elements of Cosenz’s SBMC [141], based on the work of [142].

VALUE	ECONOMIC	ENVIRONMENTAL	SOCIAL
Proposition	Economic value	Functional value	Social value
Creation I	Key Activities	Production	Governance
	Key Partners	Suppliers	Local Community
Creation II	Key Resources	Materials	Employees
	Key Partners	Suppliers	Local Community
Delivery	Customers’ Segments & Relationships	Use & End-of-Life Cycle	Society Culture
	Distribution Channels	Distribution	Scale of Outreach
Capture	Value Stream	Environmental Benefits	Social Benefits.
	Cost Structure	Environmental Impacts	Social Impacts
Sustainability Indicator	Product Innovation	Emission reduction	Human diversity
	Risk management Profit	Natural resource management Environmental management	Human rights Labor relations
	Cost savings	Environmental assessment	
Eco-Environmental	Energy efficiency		X
		Life cycle management	
Socio-Environmental	X		
		Client safety & health Global climate change	
Socio-Economic	Customer Ethics	X	Security

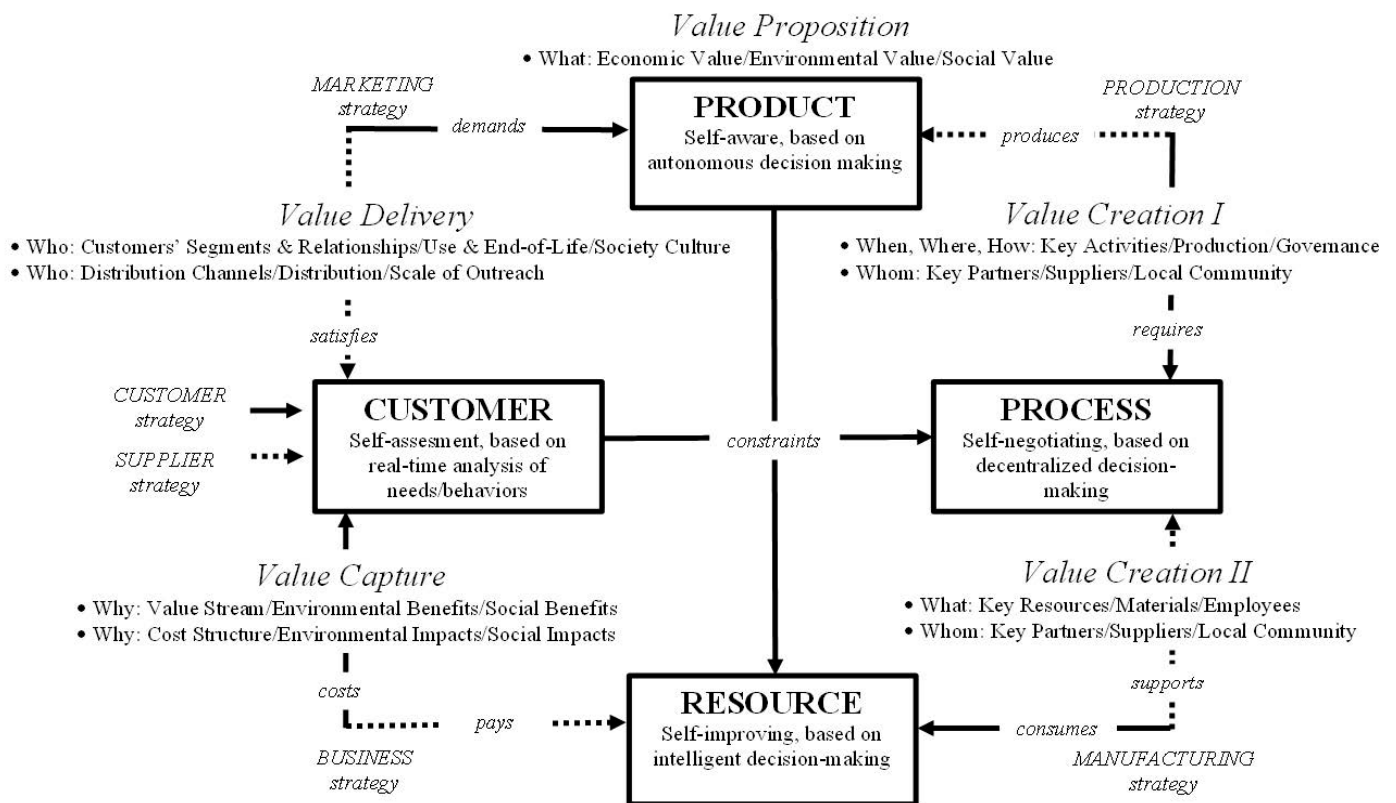


Figure 3. Sustainable CPPR 4.0 Framework (author’s original).

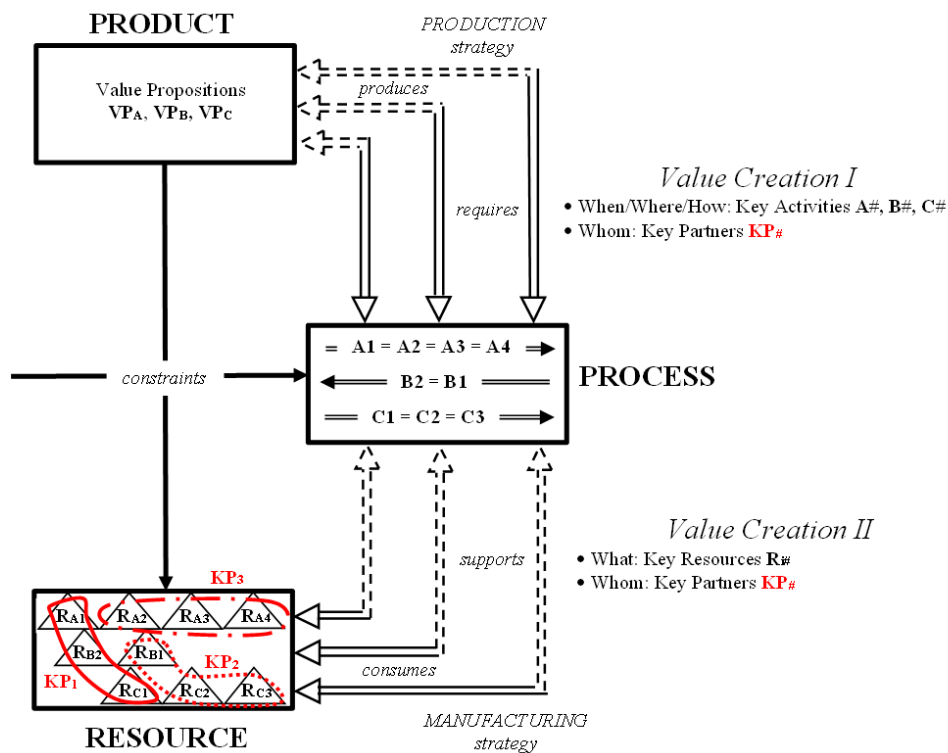


Figure 4. Value creation definition, economic value perspective (author's original).

3.2. The Value Creation Relationships

Table 3 presents the manufacturing routes of three hypothetical products presented in [134], namely A, B, and C. Figure 5 presents the manufacturing route of Product A when using a traditional strategy (left side) and a flexible strategy (right side). In the case of the traditional strategy, each machine type performs only one type of transformation process, so there are as many machine type changes as required types of transformation process. On the other hand, when following a flexible strategy, one machine type can perform two different types of transformation process. Within the context of a manufacturing system that combines both strategies, the value creation elements presented in Figure 4 are exemplified in Figure 6a (smart product) and Figure 6b (smart machine). Finally, Table 4 shows the features of these value creation relationships, and Table 5 summarizes them.

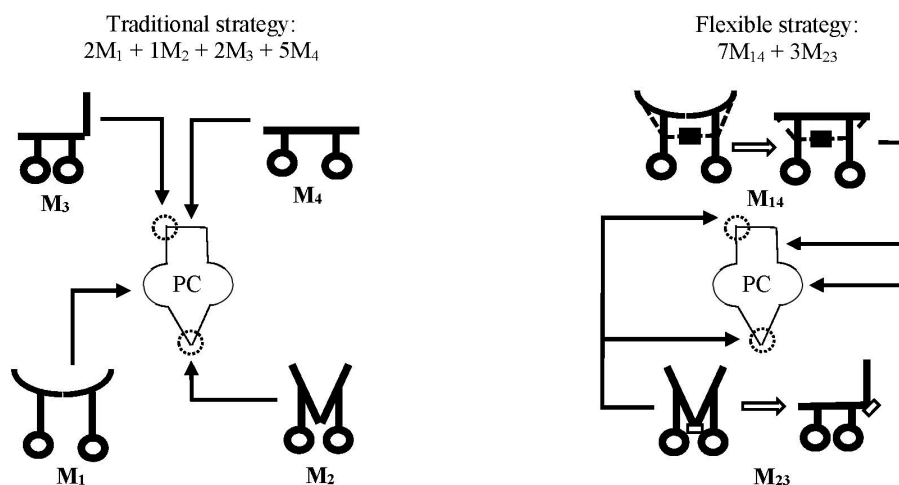


Figure 5. Traditional and flexible strategy, based on the work of [134].

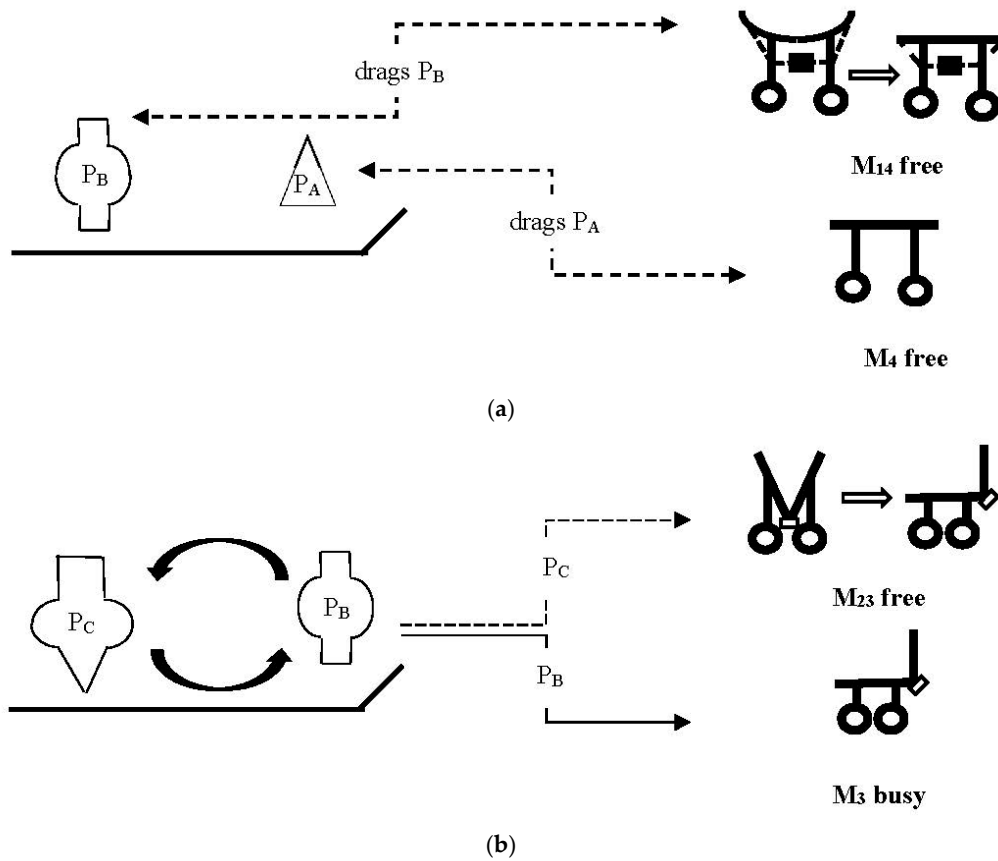


Figure 6. (a) Smart products, based on the work of [134]. (b) Smart machines, based on the work of [135].

Table 3. Manufacturing routes, Products A, B, and C, from [134].

Product	Transformation Activities Sequence						Sequence Option #	
	M1	M2	M3	M4	M14	M23		
P _A	1st			2nd			1	
	1st				2nd		2	
					1st & 2nd		3	
P _B	1st		2nd	3rd			1	
	1st		2nd		3rd		2	
	1st			3rd		2nd	3	
	1st				3rd	2nd	4	
				2nd		1st & 3rd		5
						1st & 3rd	2nd	6
P _C	1st	2nd	3rd	4th			1	
	1st	2nd	3rd		4th		2	
	1st			4th		2nd & 3rd	3	
	1st				4th	2nd & 3rd	4	
		2nd	3rd		1st & 4th		5	
					1st & 4th	2nd & 3rd	6	

Table 4. Smart process, based on the work of [134].

Product	Transformation Activities Sequence		Sequence Option #
	M4	M14	
P _A	2nd (50%)		1
		2nd (50%)	2
		1st & 2nd (100%)	3
	1/3	2/3	# sequences fulfilled
P _B	3rd (33.33%)		1
		3rd (33.33%)	2
	3rd (33.33%)		3
		3rd (33.33%)	4
		1st & 3rd (66.66%)	5
		1st & 3rd (66.66%)	6
	2/6	4/6	# sequences fulfilled
P _C	4th (25%)		1
		4th (25%)	2
	4th (25%)		3
		4th (25%)	4
		1st & 4th (50%)	5
		1st & 4th (50%)	6
	2/6	4/6	# sequences fulfilled

Table 5. Value creation relationships (author's original).

	Question Posed	Decision Criteria
Smart products	How many transformation activities are left in my manufacturing route?	Select the resource that provides the most of these transformation activities.
Smart resource	How many transformation activities can I provide?	Select the product that consumes the most of these transformation activities.
Smart process	Which combination of product and resource advances my manufacturing route completion the most?	Select the combination that advances the most manufacturing routes.

Smart products (VP_A , VP_B , and VP_C in Figure 4); where products “talk” to each other and select the most convenient manufacturing resources, depending on the transformation activities left to be performed on their respective manufacturing routes. For example, in Figure 6a, P_B is the first in turn to use machine M_{23} for its second transformation operation, representing 33.33% of its manufacturing route. However, if P_C uses machine M_{23} , for its second and third transformation operations, that would cover 50% of its manufacturing route. In this case, P_B “agrees” to wait for machine M_3 to become free and let P_C use machine M_{23} first.

Smart machines (R_{Ai} , R_{Bi} , R_{Ci} in Figure 4); where manufacturing resources “talk” to each other, and select the most convenient product to process, depending on the transformation activities each of them can perform. For example, in Figure 6b, P_A is the first in turn to use either machine M_{14} or M_4 for its second transformation operation, representing 50% of its manufacturing route. However, if P_B uses machine M_{14} , for its first and third transformation operations, that would cover 66.66% of its manufacturing route. In this case, M_{14} “agrees” to process P_B , leaving P_A to be processed by M_4 .

Smart process (A_i , B_i , C_i in Figure 4); where the manufacturing routes “talk” to each other and give priority to the one for which the most convenient combination of product and manufacturing resource are in place. For example, in Table 4, the manufacturing route of P_B benefits the most if it is assigned the use of machine M_{14} , as it would cover four out of six possible potential transformation activities sequences, where in two of them, the advance would be in 66.66%. In this case, the manufacturing routes of P_A and

P_C “agrees” to this assignment, and later on, P_C “agrees” to the assignment of machine M_4 to the routing process of P_A , as this would cover one out of three possible potential transformation activities sequences, the same case for P_C , but with an advance of 50% (versus 25% of product P_C).

3.3. The Value Creation Abilities

On the other hand, [89] proposed a set of necessary abilities to support value creation, grouped under the SC C^4 concept (Figure 7):

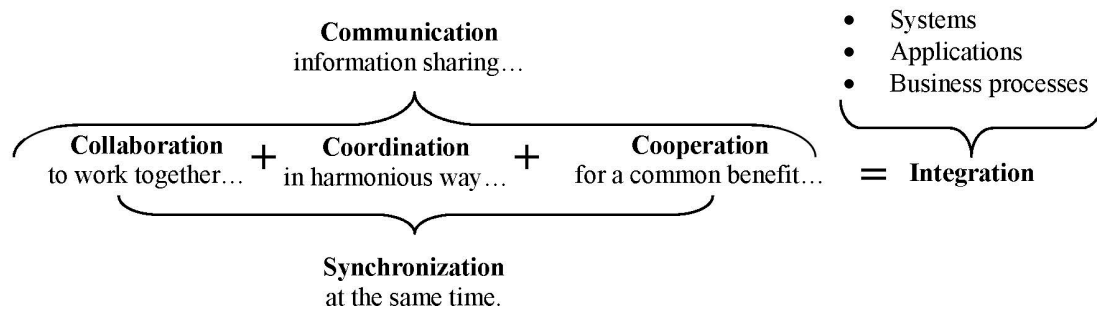


Figure 7. The SC C^4 concept, based on the work of [89].

Communication, the ability to share key and relevant information with the rest of the involved partners. This is possible when the means to provide free information flow/access are in place.

- Collaboration, the ability to work together by adjusting the individual behavior of the involved partners. This is possible when the means to negotiate common benefits and risks sharing are in place.
- Coordination, the ability to work in a harmonious way when pursuing a goal that is common to all of the involved partners. This is possible when the means to match individual actions with common decision-making processes are in place.
- Cooperation, the ability to work for a common benefit in terms of an objective that is feasible to all of the involved partners. This is possible when the means to align the individual operational levels with the common strategic levels are in place.

These value creation abilities can be examined from the point of view of the value creation relationships (Figure 4), or termed from now on as sustainable value creation C^4 :

1. Communication, the ability to share key and relevant information to the rest of the involved partners. In this case, the involved partners refer to the smart products, process, and resources. In the case of information, we propose the definition proposed by [143]:
 - Information: data (detected signal that shows a non-random quantified pattern) that have been evaluated to have relevance and used for establishing a course of action to implement defined objectives.

From the DT perspective, this means that there must be a mechanism in place that allows the smart products, processes, and resources “to talk among themselves and understand each other”, with the purpose of establishing a common objective. In Figure 8, the “ontology and semantics” element represents the means through which the DT allows interactions of the elements of the physical world.

2. Collaboration, the ability to work together by adjusting the individual behavior of the involved partners. This is possible when the means to negotiate common benefits and risks sharing is in place. In the case of behavior, we propose the definition proposed by CIMOSA, the Computer Integrated Manufacturing–Open Systems Architecture [144], when referring to the behavior of a process:

- Behavior: defined by a set of procedural rules that dictate how actions/activities need to be done/executed. This behavior is intended for the achievement of some objective, under some constraints, using some resources. A procedural rule can be in the form of a triggering condition (i.e., a system state) or an event (that is, a solicited request/unsolicited real-world happening which initiates the execution of an action/activity).

From the DT perspective, this means that there must be a mechanism in place that allows the smart products, processes, and resources “to define” a combined set of procedural rules that “guides” the pursuing of the common objective, within the upper limit of the benefits and the lower limit of the risks (Figure 9).

3. Coordination, the ability to work in a harmonious way when pursuing an objective that is common to all of the involved partners. This is possible when the means to match individual actions with common decision-making processes are in place. In the case of decision-making, the structure of a GRAI net (Figure 10, Table 6), which is basically a Petri net with special graphical symbols [145], could be used to represent it. From the DT perspective, this means that there must be a mechanism in place that allows the smart products, processes, and resources “to visualize” the impact of the individual decision-making processes, therefore, the next action/activity that needs to be done/executed can be determined properly.
4. Cooperation, the ability to work for a common benefit in terms of a goal that is feasible to all of the involved partners. This is possible when the means to fit/integrate the individual contributions with the overall result are in place. From the DT perspective, this means that there must be a mechanism in place that allows the smart products, processes, and resources, “to integrate” their individual contributions, so the placing (where)/timing(when) of the next action/activity that needs to be done/executed can be determined properly.

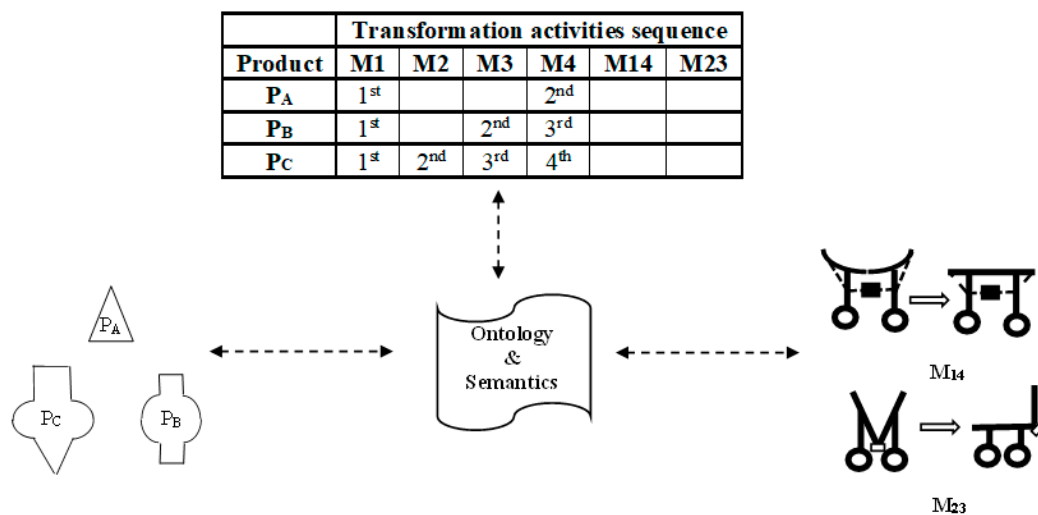


Figure 8. Communication ability (author’s original).

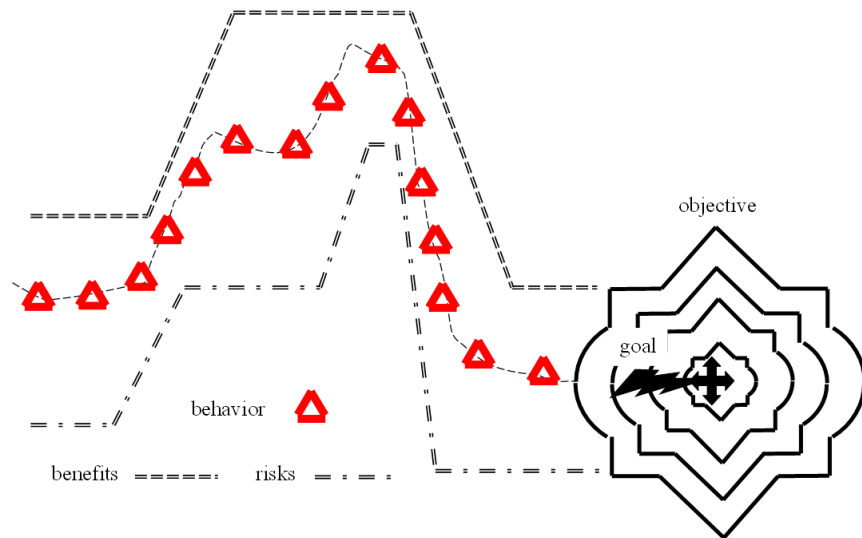


Figure 9. Collaboration ability (author’s original).

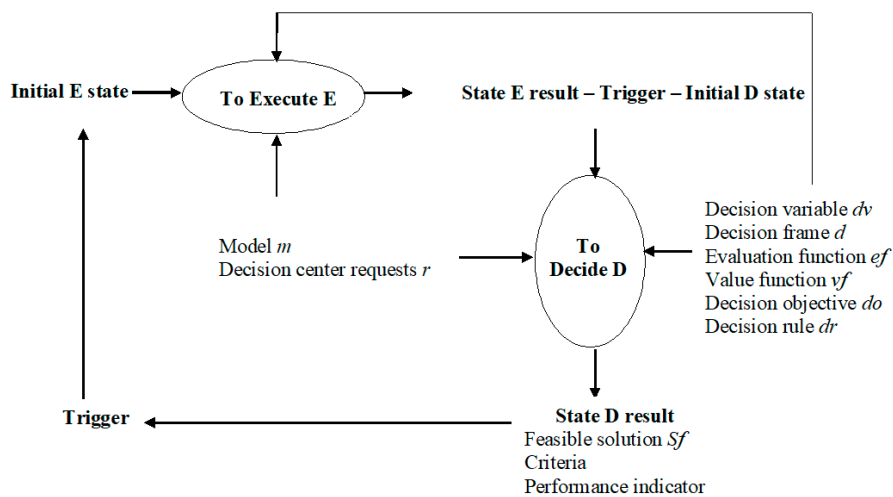


Figure 10. Coordination ability (GRAI net structure).

Table 6. GRAI net elements and terminology.

Elements	Terminology
Model m	Structure and parameters describing the Decision problem d .
Decision variable dv	A vector of the variables of the Decision problem d .
Decision frame d	Set of all solutions Sd of the decision center for a given Decision problem d .
Decision center requests r	Restrictions issued/constraints imposed on the solution space by a decision center.
Feasible solution Sf	For a given Model m , Decision frame d , and Decision center requests r , a set of all instantiations of Decision variable dv .
Evaluation function ef	Function which assigns a real value to each feasible solution sf .
Value function vf	Function which combines the values of all Evaluation functions ef , of several Decision objectives do , to define one scalar value for a given Feasible solution sf .
Decision objective do	Minimization or maximization of an Evaluation function ef .
Decision rule dr	For a given Model m , Decision frame d , Decision center requests r , an algorithm which finds a good Feasible solution Sf with respect to the Decision objective do .

4. The SMC4.0 Information Flow Model

The basis for fulfilling the needs of a mass customization environment is based on the analysis of the data generated in increasing volume, variety, and velocity that enhances/improves the decision-making process at the different manufacturing stages [100]. This information has different views, namely forecasting, quoting, order specification, scheduling, production, finished product, historical records, and revival for warranty or service [146]. Moreover, the integration of the Industry 4.0 concept with mass customization requires one to implement communication between machines, between product and machine, between humans and machines, and between the manufacturing system and the customer [7]. Table 7 presents a summary of different mass customization business processes: the design–sell–make–assemble cycle proposed by [147,148], the product development–order taking–order fulfilment (management and realization) fundamental processes proposed by [146,149,150], and the five step sequence for the execution of the mass customization approach within an Industry 4.0 environment proposed by [34].

On the other hand, [146,151] mention that the mass customization paradigm often uses a Make-to-Order (MTO) approach. The authors of [152,153] agree with this, due to the fact that an MTO approach is a business production strategy that allows consumers to purchase products that are customized to their specifications, and where the manufacturing of an item begins only after a confirmed customer order is received. For this reason, [99] refers to the output of a mass customization production system, operating within an Industry 4.0 context, as “customer-specific, make-to-order” products. The authors of [154] use the term digital MTO when talking about mass customization operating in the context of Industry 4.0. As we are interested in determining the basic structure of the information flow model that will support the operation of SMC4.0, we propose to take the value domains of the proposed sustainable CPPR 4.0 framework, and map them into the MTO mass customization business processes proposed by [36,146–150], and the sub-cycles/activities that define the MTO approach, as proposed by [155]. Moreover, we propose to focus only on the order fulfillment business process (highlighted in yellow in Table 7), as this is the one that corresponds to the value creation section of the Sustainable CPPR4.0 framework (Figure 4). By proceeding in this way, we can address DT’s imperative of having a mechanism in place that allows for high levels of sustainability (result of successful/efficient manufacturing execution), via the proper linking/alignment of both the strategic/operational levels of a mass customization manufacturing organization.

Table 7. MTO-based mass customization business processes (author's original). In this way, the set of mass customization structural elements (highlighted in yellow, in Table 8), proposed by [131], can be used to reflect the strategic/operational alignment conditions within the context of the mass customization paradigm environment. This set of structural elements have proved to be useful in the development of a system dynamics model for the purpose of analyzing the demand fulfillment capability of a mass customization manufacturing environment. In this work, demand fulfillment was understood in terms of achieved production volume and was the result of a combination of a different level of customization and level of system reconfiguration values. Appendix B (Figure A1, Table A1) offers the details of the relationships among the structural elements in terms of a Casual Loop Diagram (CLD), as well as a description of each one.

Sustainable CPPR 4.0		Mass Customization Business Processes			Make-to-Order	
[131]	[147,148]	[146]	[149,150]	[34]		[155]
					Subcycles	Activities
Value Proposition	Design	Product development/design	Development; i.e., product development/design	Step #1: personalization	Design	Design new products
						Conduct market research
						Analyze product technology
						Develop prototype
						Design new components
Value Capture	Sell	Order taking	Interaction; i.e., order placement	Step #2: purchasing	Order processing	Create sales order
						Modify standard design to meet customer requirements
						Obtain customer approval for new design
						Develop bill of material and process plans
						Respond to customer inquiry
Value Creation	Make/Assembly	Order fulfillment management	Production; i.e., fabrication/assembly	Steps #3 and #4: manufacturing	Production	Develop specifications
						Determine delivery
						Determine price
						Check customer credit
						Receive customer approval
Value Delivery	N/A	Order fulfillment realization	Logistics; i.e., packing/delivery	Step #5: delivering	Distribution	Production planning and control
						Materials management
						Fabricate parts
						Assemble products
						Inspection, testing, rework
						Inventory finished products
						Ship products to distribution center
						Pick products for customer orders
						Ship products and invoice customers

Table 8. Mass customization structural elements, value creation context (author’s original).

Mass Customization Structural Elements [134]	MTO Business Model [155]	
	SUBCYCLES	ACTIVITIES
Level of customization	Design	Design new products
Level of OW/OQ		Conduct market research
Level of product’s complexity	Design	Analyze product technology
		Develop prototype
		Design new components
		Modify standard design to meet customer requirements
		Obtain customer approval for new design
Level of production volume	Production	Develop bill of material and process plans
		Production planning and control
		Materials management
		Fabricate parts
		Assemble products
		Inspection, testing, rework
Level of production variety	Production	Inventory finished products
Level of technification		
Level of labor skill		
Level of system’s reconfiguration		
Level of components/raw materials		

Managerial Implications

Small-to-Medium Enterprises (SMEs) have a high impact on the overall economy of many countries, something that has been reported frequently in the literature. However, how they could participate in a SMC4.0 environment imposes several challenges. SMEs need to adapt their business models and implement Industry 4.0-related technologies [156], which in turn results in a struggle to obtain the required resources/knowledge, i.e., standards and norms foreign to them [50], for successful adaptation/implementation [22]. This creates a false perception that this level of advanced automation is reserved to big industrial players [157]. Additionally, SMEs have no clear idea of how the strategic business level and operational technological level are related and should be linked [158]. It is our belief that a DT developed for the case of the SMC4.0 environment, can be used as a what-if scenario testing tool, so the proper balance between capital investment and sustainable profitability can be assessed.

5. Concluding Remarks

5.1. Future Research

As stated previously, in order to truly operationalize the SMC4.0 concept, it is required to understand this in terms of both a business and manufacturing environment. As the first step towards this goal, future research should focus on the development of the sustainable value creation C⁴ mechanisms:

- A mechanism for smart products, processes, and resources, “to talk among themselves and understand each other” (Communication);
- A mechanism for smart products, processes, and resources, “to define” a combined set of procedural rules that “guides” the pursuing of the common objective (Collaboration);
- A mechanism for smart products, processes, and resources, “to visualize” the impact of the individual decision-making processes (Coordination);
- A mechanism for smart products, processes, and resources, “to integrate” their individual contributions (Cooperation).

These mechanisms, once developed, could be tested using the DT capabilities to “recreate” the physical world, in order to test their validity, before being implemented in the real physical world.

5.2. Conclusions

Business enterprises all around the world are facing the challenge of moving from a mass production market to the mass customization one. In the latter, customers have the opportunity to design their own products/services without paying a high price premium. These challenges require companies to develop new value creation business models, based on the integration of technological innovations that promote the value-creation from exploiting available data. Digital Twins (DTs) are one of the disruptive technologies-associated with the Industry 4.0 concept which synchronizes the physical and digital, and with these allows one to address the issue of manufacturing customized products. Some relevant concepts related to the role of DTs in the achievement of sustainable value creation within a mass customization 4.0 environment were reviewed. Derived from this exercise, the Sustainable CPPR 4.0 framework was introduced as the ultimate success within the mass customization paradigm which depends on its level of sustainability, achieved through the use of an efficient manufacturing processes. The Sustainable CPPR 4.0 framework was used to analyze the set of relationships and abilities that support the value creation process, and in each case, the implications from a DT perspective were discussed. Finally, a CLD showing the relationships among the mass customization structural elements that reflect the strategic/operational alignment conditions within the context of the mass customization paradigm environment was presented. The idea behind the CLD is to serve as a basis for the information flow model to assure successful/efficient manufacturing execution.

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Appendix A

Industry 4.0-related technologies can have a positive role in boosting sustainable performance [159]. For example, the digitalization/interconnection of all production areas is a key facilitator in the efficiency of industrial processes, i.e., reduction of waste generation through its recycling [160], as well as efficient management of energy consumption [161,162] enabling the adoption of a circular economy [106]. Within this, products can be disassembled into their component elements for reuse, recycling, or remanufacturing [105,163]. This is possible due to the use of a smart factory, that allows controlling and analyzing the life cycle of any product within/outside the manufacturing area in a transparent and integral way [164]. In general, Industry 4.0 can help to meet the environmental, economic, and social targets of sustainability [165]:

- From an economic point of view, Industry 4.0 technologies can reduce set-up times, achieve shorter lead times, reduce labor and material costs, increase production flexibility, achieve higher productivity, and enhance customization [166];
- From an ecological point of view, Industry 4.0 technologies can reduce energy/resource consumption through detection/data analysis across production/supply chain processes [167] and lead to reduction in waste/CO₂ emissions through data-centered and traceable carbon footprint analyses [168];
- From a social point of view, Industry 4.0 technologies can support employee health and safety, by taking over monotonous and repetitive tasks resulting in higher employee satisfaction and motivation [21].

Now, within the United Nations Sustainable Development Goals (or SDGs), for firms, industries, and countries to achieve sustainable development [169], Industry 4.0 technologies have the potential to benefit all of the seventeen SDGs [170]:

- Economic sustainability attributes; end poverty (EP), decent work and economic growth (DWEG), industry, innovation, and infrastructure (III), reduced inequalities (RI), and partnerships for the goals (PG).

- Social sustainability attributes; end hunger (EH), good health and well-being (GHW), quality education (QE), gender equality (GE), and peace, justice and strong institutions (PJSI);
- Environmental impact attributes; clean water and sanitation (CWS), affordable and clean energy (ACE), sustainable cities and communities (SCC), responsible consumption and production (RCP), climate action (CA), life below water (LBW), and life on land (LL).

The reader interested in the specific Industry 4.0 technology that impacts each one of the 17 SDGs can consult Table 2 in [170]. Even though there are few studies that provide insight into the interface between Industry 4.0 technologies and sustainability, ref [171] makes a review of these studies.

Appendix B

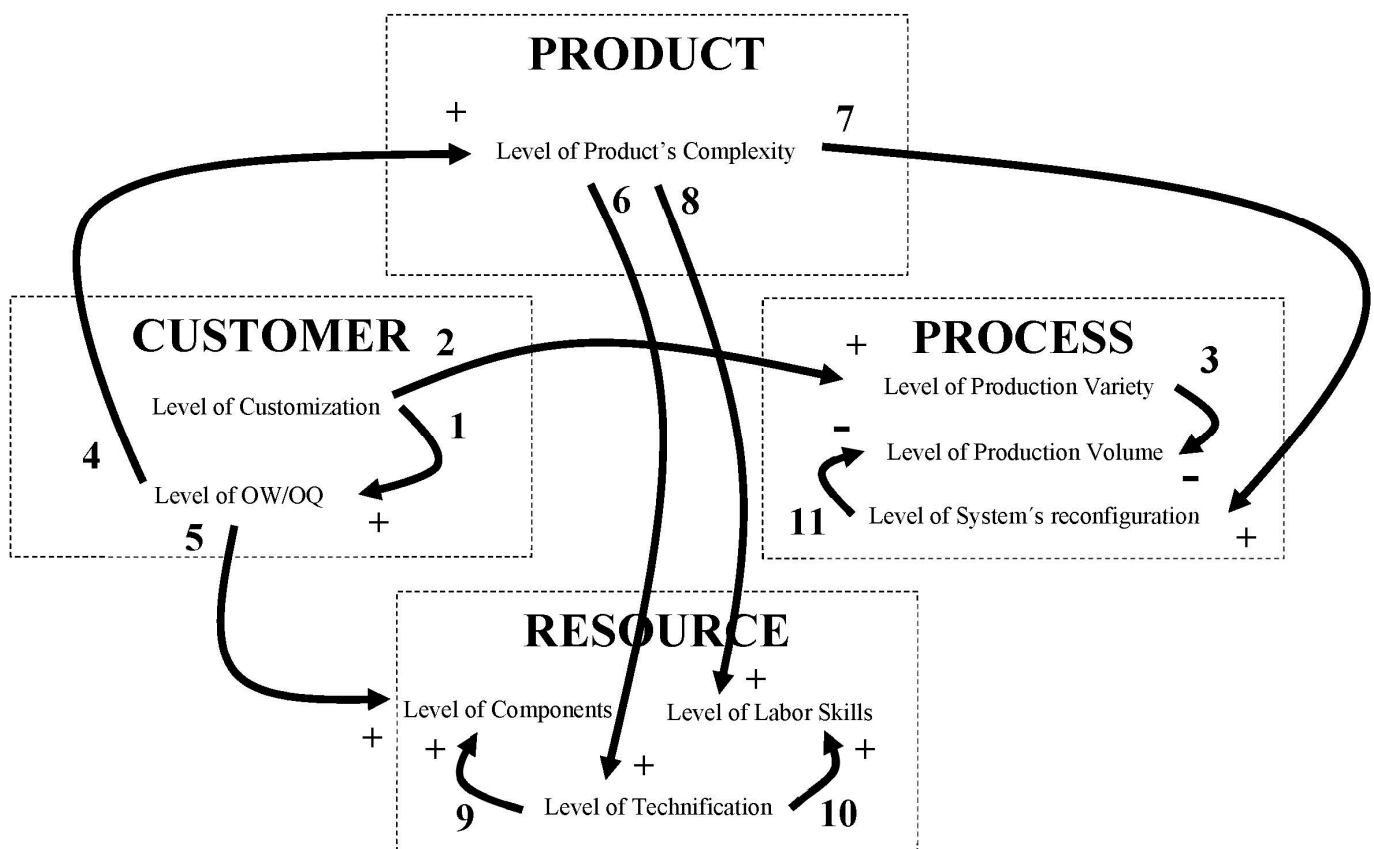


Figure A1. Mass customization structural elements-CLD relationships (author's original).

Table A1. CLD relationships' definition (author's original).

Mass Customization Structural Elements	Range of Values		Rn *	From	To	Rt **
	0	1				
Level of customization (lc)	Standard product	Personalized product	1	lc	lowoq	+
Level of OW/OQ (lowoq)	100% Common features	100% Unique features	2	lc	lpva	+
Level of product's complexity (lpcplx)	Few operations/easy to execute	Lot of operations/hard to execute	3	lpva	lpvo	–
Level of production variety (lpva)	A small number of models	A large number of models	4	lowoq	lpcplx	+
Level of production volume (lpvo)	A few units produced	A lot of units produced	5	lowoq	lcomp	+
Level of system's reconfiguration (lsr)	Hard-connected workstations/rigid flow	Loose-connected workstations/flexible flow	6	lpcplx	ltech	+
Level of equipment technification (ltech)	Specialized-use equipment	General-use equipment	7	lpcplx	lsr	+
Level of labor skill (ls)	Single-task specialist	Multiple-task generalist	8	lpcplx	ls	+
Level of components (lcomp)	Small number of components	Large number of components	9	ltech	lcomp	+
Level of customization (lc)	100% Common features	100% Unique features	10	ltech	ls	+
Level of OW/OQ (lowoq)	Few operations/easy to execute	Lot of operations/hard to execute	11	lsr	lpvo	–

Rn * Relationship number; Rt ** Relationship type (positive +; negative –).

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