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The role of manufacturing efficiency in the achievement of sustainable mass customization 4.0

César Martínez-Olvera

Escuela de Ingeniería, CETYS Universidad, México

ABSTRACT
One of the goals of the Industry 4.0 paradigm is the sustainable success within a mass customization environment, which in turn, depends on the manufacturing efficiency of the transformation processes. In this paper we propose to represent manufacturing efficiency within the context demand fulfillment. The main original contribution of this paper are two demand fulfillment analytical expressions. Their novelty is on the way they are expressed, that is, in terms of the structural elements that define a mass customization environment. Their usefulness was put to the test via a Discrete Event Simulation (DES) model of two different demand fulfillment strategies (namely inventory-oriented level and capacity-oriented chase strategies). The obtained results suggest that the analytical expressions act as a fairly good trend indicator of the missed demand values increase/decrease. A discussion of the managerial implications of these findings are presented at the end of this document.

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Industry 4.0; manufacturing efficiency; mass customization; simulation; sustainability

1. Introduction

The central idea behind the Industry 4.0 paradigm is the implementation of a fully automated and digitalized production environment (Duarte & Cruz-Machado, 2018), by combining technologies such as the Internet of Things (IoT), Big Data, and Cyber-Physical Systems (CPS), which in turn have clear sustainability implications (Junior et al., 2018). Appendix A discusses some of the different Industry 4.0 reference architectures that have been proposed by both the Academia and the Industrial practitioners, for those readers interested into this topic. Now, this way of operating has a direct impact in the customer relationship business process, as the customer now has the opportunity of tailoring of products and/or services (Cornelis de Man & Strandhagen, 2017). This last relates directly to the mass customization paradigm, which consists on giving the customers the opportunity to design and define their own individual products and/or services (Duarte & Cruz-Machado, 2018). At this point, and before proceeding further, it is important to observe the difference between mass customization and mass individualization, a paradigm that shares the same three basic actions of mass customization –

CONTACT César Martínez-Olvera cemarol@gmail.com Escuela de Ingeniería, CETYS Universidad, México

namely, design the product, make the product, and sell the product – but in a different sequence and in the customer's role and involvement in buying the product. According to Koren et al. (2016), (2015):

- In mass customization, all modules are designed by the product manufacturer and offered to customers as optional product choices, the customer selects the modules, pays for the product, and then the final product is made and delivered.
- In mass individualization, the manufacturer designs the product platform with a large variety of possible interfaces for new modules, and defines the interfaces, the customer selects a platform and searches on the Internet for desired certified modules that fit the selected platform, pays for the platform as well as for the selected modules, and then the modules are sent to the manufacturer and the final product is made and delivered.

Moreover, it has been stated that the central notion of Industry 4.0 is a quick response to the demand of highly customized products, in and profitable way, and considering the environmental and social impacts that guarantees a durable competitiveness (Dziurzanski et al., 2018). In this way, the goal of Industry 4.0 – among several others – becomes the sustainable success in a mass customization market (Blecker & Friedrich, 2007), (Latorre-Biel et al., 2018), where the customers' requirements increase in diversity (Efthymiou et al., 2012), (Man & De Strandhagen, 2017), as products are designed to their individual specifications (Duarte & Cruz-Machado, 2018), (2017, 2017) via the combination of functions and components (Pfisterer et al., 2016), and without having to pay a high price premium (Fan-Tien et al., 2000), (Zawadzki & Zywicki, 2016), (Sievänen et al., 2010). Finally, manufacturing enterprises have to find new ways to produce 'more with less', as the result from the pressure of customers demanding for eco-efficient manufacturing processes (Heilala et al., 2013), (Mishima, 2013), (Fysikopoulos et al., 2014). This eco-efficiency refers to producing the same amount of products in the right time, with the right quality consuming less energy (Stich et al., 2013), (Li, 2015), an important aspect of sustainable development (Kang, 2016). As the sustainability payoff – the proper balance between the economic and environmental perspectives (Gabriel & Pessl, 2016), (Thiede, 2018) – is inherent to an Industry 4.0 environment, next section reviews the relationship between the Industry 4.0, Manufacturing Efficiency, and Sustainability topics. Derived from this literature review, we proceed to enunciate our research features: (1) research gaps and opportunities; (2) research proposal (3) proposed research methodology; and (4) research originality, usefulness, validity, and contributions.

2. Literature review

2.1. Manufacturing efficiency

According to Ivanov (2018), the proper or poor alignment among the strategic and operational levels of a manufacturing organization, affects the overall performance. For this reason, it becomes necessary to take that issue into account, as the achievement of high levels of sustainability derives from avoiding a poor efficiency in both the

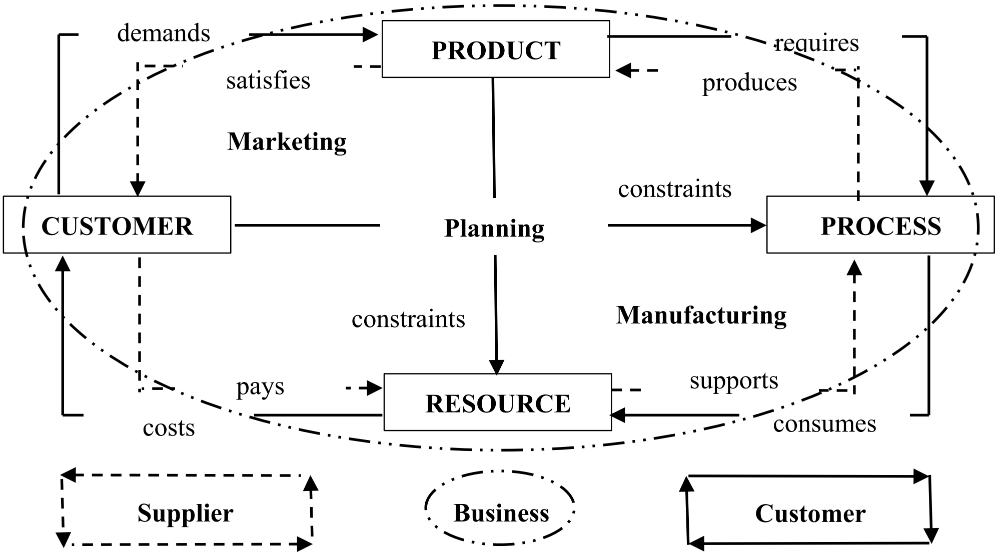


Figure 1. The CPPR framework (Martínez-Olvera et al., 2006).

managerial and transformation processes. The Customer–Product–Process–Resource (CPPR) framework (Figure 1), proposed by Martínez-Olvera et al. (2006), is a comprehensive framework that represents a manufacturing enterprise from a SC standpoint, via a set of structural elements and configuration variables. Within the CPPR framework, there is a set of within-and-among alignment conditions (Martínez-Olvera, 2008) necessary for the proper alignment between the strategic and operational levels of manufacturing organization. This proper alignment is a necessary condition for the achievement of the manufacturing efficiency of the transforming processes (Martínez-Olvera & Davizon-Castillo, 2015), (Cornelis de 2017). The use of the CPPR framework has been extended in order 1) to establish the set of documents that promote proper manufacturing execution and, with this, an efficient performance (Martínez-Olvera, 2007); 2) to put establish the set of structural elements that define a mass customization environment (Martínez-Olvera et al., 2019).

2.2. *Sustainability & industry 4.0*

Sun et al. (2012), Brettel et al. (2014), and 2016 mention the opportunities of Industry 4.0 for achieving sustainability. Jabbour, Jabbour, Foropon et al. (2018, 2018) consider that Industry 4.0 has clear implications for sustainability in organizations. Yadav et al. (2020) introduced the notion of a framework to achieve sustainability in manufacturing organisations of developing economies. A. Jamwal et al. (2021a) proposes a sustainability-based Industry 4.0 framework for MSMEs in for emerging economies. Davis et al. (2012), Kang et al. (2016), and 2018 state that a promise of Industry 4.0 – through the use of the so-called smart manufacturing systems – is that it will make it possible to achieve higher agility, productivity, and sustainability levels. Yoon et al. (2012) mentions sustainability as one of the three main requirements of a smart factory. Wang (2016) contends that a smart factory would help implement the sustainable production mode to cope with global challenges. Kusiak (2017a) presents sustainability as one of six pillars considered to be important in setting up smart factories.

On the other hand, Zipkin (2001) and Andersen et al. (2017) state that a critical enabler for an efficient mass customization is the process flexibility of the production system – that is the capability to offer product mix and changeover (Blecker & Friedrich, 2007) – as it allows a fast and easy reconfiguration of production facilities (Dhungana et al., 2017). However, the higher process flexibility is, the more difficult it is to achieve a high manufacturing efficiency, an issue that can be properly address by the use of automation (Gullander et al.,). From here the idea of addressing the mass customization challenge through the use of an Industry 4.0 environment (2018), (Yao et al., 2019), (Mourtzis et al., 2018), more specifically, the use of a CPS-based smart manufacturing system, which in turn, according to Thiede (2018), there is an 'environmental backpack' due to the introduction of CPS-related components.

For a more extensive discussion of the relationship and link between Industry 4.0 and Sustainability, the reader is referred to R. Jamwal et al. (2021b).

2.3. Sustainable mass customization 4.0

The concept of Sustainable Mass Customization 4.0 (SMC4.0), introduced by Martínez-Olvera and Davizon-Castillo (2015) summarizes the ideas stated in the previous sections: a mass customization environment that focuses in the production of short lead time, tailored products – based on a re-configurable smart CPS, where the sustainability element is derived from the manufacturing efficiency of the transformation processes (Yao et al., 2019), (Bordeleau et al., 2018), (2018), (Mourtzis et al., 2018), (Ghobakhloo, 2020) that in turn, allows an optimal resource and energy productivity/efficiency (Otto et al., 2014), (Lachenmaier et al., 2017). A transformation process can be understood as the value creation chain of steps necessary to transform the input material's form, shape, and/or properties into the output finished products, in the face of environmental impacts derived from the consumption of energy and other auxiliary resources (Li, 2015).

2.4. Research features

Based on the literature review (Table 1), the previous section can be summarized as follows: one of the goals of a SMC4.0 system – defined in this paper as a mass customization production system operating within a re-configurable CPS context – is to achieve high levels of sustainability, which can be achieved by the manufacturing efficiency of the transformation processes (understood these last as a set of value creation process chains). Derived from this finding, we identify the following research opportunity: to establish the SMC4.0 paradigm in the context of an energy-efficient, manufacturing process chain. This last can be stated as the following research question: is there a way to quantify the ability of a manufacturing organization to produce 'more with less' (for the case of a mass customization environment), so manufacturing efficiency can be expressed within a sustainability context? Following this idea, we

Table 1. Literature review summarizing table.

Sustainability and . . .	References
Industry 4.0	Davis et al. (2012), Sun et al. (2012), Yoon et al. (2012), Brettel et al. (2014), Kang et al. (2016), 2016, Wang (2016), Kusiak (2017a), Jabbour, Jabbour, Foropon et al. (2018, 2018b), 2018
Mass Customization	Lachenmaier et al. (2017), Dziurzanski et al. (2018), Latorre-Biel et al. (2018)
Manufacturing Efficiency	Heilala et al. (2013), Mishima (2013), Stich et al. (2013), Martínez-Olvera and Davizon-Castillo (2015), Cornelis de Man and Strandhagen (2017), Thiede (2018)

state our research proposal to be the development of an analytical expression that quantifies manufacturing efficiency for the case of a mass customization environment. In order to accomplish our research proposal, we propose to proceed in the following way: use the CPPR framework to express the demand fulfillment feasibility equations – presented by Martínez-Olvera et al. (2006) into the context of a mass customization environment. These equations act as an indicator of the demand fulfillment feasibility (ability a manufacturing organization has to achieve a demanded volume), one of many ways on which manufacturing efficiency can be assessed. The original contributions of the research work proposed in this paper are two: 1) A Casual Loop Diagram (CLD) that establishes the relationships derived from the set of structural elements that define a mass customization environment; 2) the proposed demand fulfillment analytical expression, for the case of a mass customization environment. The rest of the paper is organized as follows: Section 3 presents the presents the theory foundation behind the demand fulfillment analytical expression, for the case of a mass customization environment. The usefulness and validity of the analytical expression is demonstrated in Section 4, where the development of a discrete-event simulation (DES) model of a hypothetical mass customization production system allows testing different operational conditions, in order to compare the obtained results with those ones obtained by the analytical expression. A discussion of the managerial implications of the obtained results is presented in Section 5, together with the final conclusions and the identified future research venues.

3. Mass customization manufacturing efficiency

3.1. Mass customization casual loop diagram (CLD)

In his work of 2019, Martínez-Olvera proposed the use of the CPPR framework to establish a set of structural elements that define a mass customization environment (Table 2). In this section, we expand this work to derive a Casual Loop Diagram (CLD) that establishes the relationships derived from those structural elements (Figure 2). Tables A and B (in Appendix B), explain the rationale behind these relationships, and express them in terms of a System Dynamics (SD) model equations (the development of such model is an area of opportunity that will be explored in future research).

Table 2. Mass customization structural elements (Martínez-Olvera et al., 2019).

Element #	CPPR Context	Mass Customization Context
1	Level of required customer feedback	Level of customization
2	OW/OQ ratio	Level of OW/OQ
3	Number of operations/components	Level of product's complexity
4	Level of production volume	Level of production volume
5	Level of product variety	Level of production variety
6	Level of technology specialization	Level of technification
7	Level of labor skills	Level of labor skill
8	Level of process flexibility	Level of system's reconfiguration
9	Level of raw material requirements	Level of components/raw materials

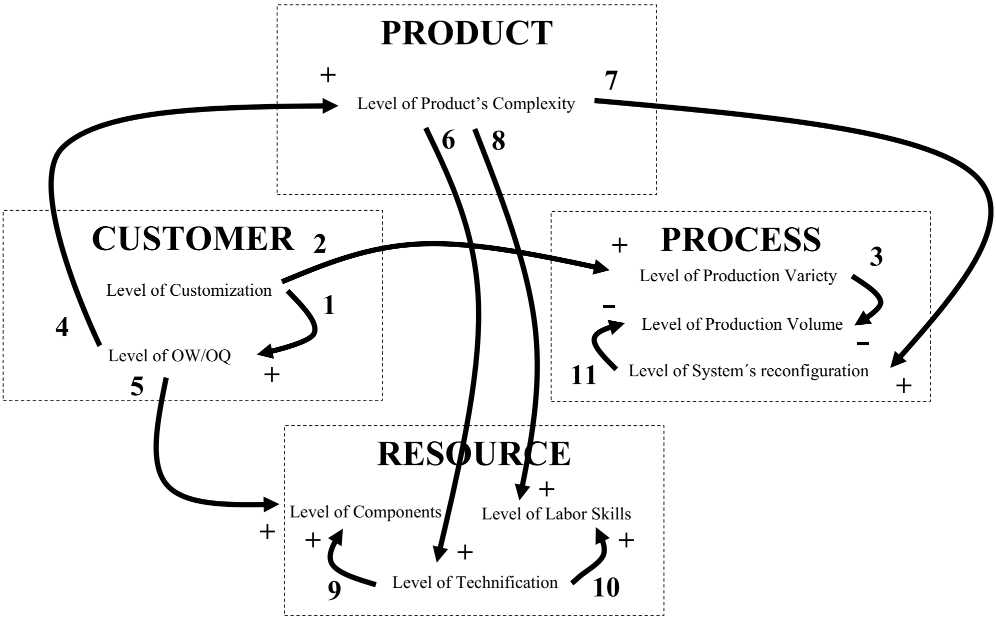


Figure 2. Mass customization CLD relationships (Source: author constructed).

3.2. Demand fulfillment and manufacturing efficiency

According to Chen (2008), the performance of a manufacturing organization can be expressed in terms such as customer satisfaction, product quality, speed in completing manufacturing orders, productivity, diversity of product line, flexibility in manufacturing new products, etc. Following this idea, of reflecting the performance of a manufacturing organization, Cesar Martínez-Olvera (2010) proposed the use of two demand fulfillment formulations (Equations 1 and 2):

$$Inventory\,contribution = D * (1 - U) * (1 - BM) * (1 - F) * S \qquad (1)$$

in this way, when demand uncertainty is low (U = 0), a business model make-to-stock is recommended (BM = 0), and an inventory-oriented level strategy should be used. This strategy requires the use of a rigid continuous production line, where the process environment flexibility is low (F = 0), as the special-purpose equipment used allows to profitably manufacture high-volumes of products with high standardization (S = 1).

$$Capacity\,contribution = D * U * BM * F * (1 - S) \quad (2)$$

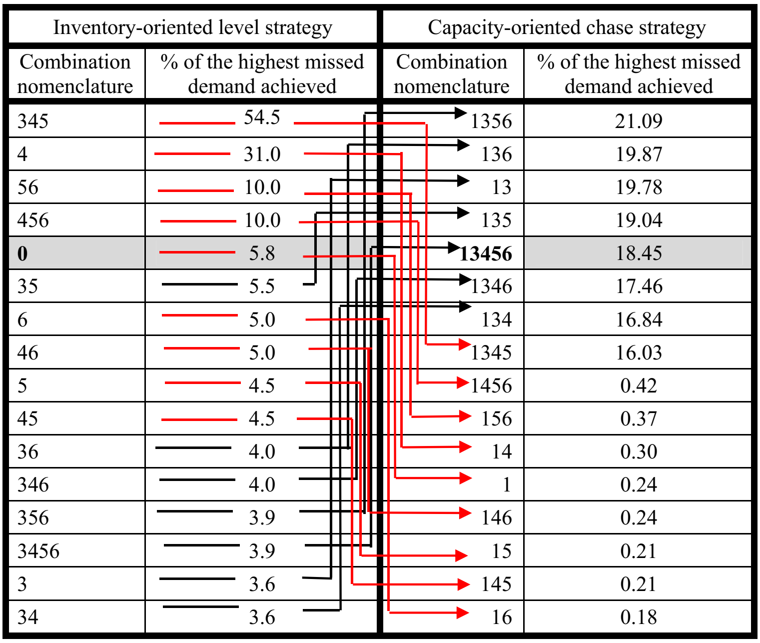
in this way, when demand uncertainty is high (U = 1), a business model make-to-order is recommended (BM = 1), and a capacity-oriented chase strategy should be used. This strategy requires the use of a flexible job shop, where the process environment flexibility is high (F = 1), as the general-purpose equipment used allows to profitably manufacture low-volumes of products with low standardization (S = 0).

Equations 1 and 2 represent the contributions made by the inventory-oriented and capacity-oriented strategies to the fulfillment of a certain demand level D, where the closer the result is to this last, the more feasible it will be for the manufacturing organization to achieve the demanded volume (and it must not be taken as an estimator of the final values of the fulfilled demand). One of the findings of this study was that the same total backlog values (i.e. the amount of unfulfilled demand) can be obtained through different combinations of **U, BM, F**, and **S**. It is our belief that these equations can be used to represent manufacturing efficiency, as they can be used to determine the optimal **U, BM, F**, and **S** levels that would allow achieving a high frecuency of lower total backlog values (that is, produce 'more with less', the core concept behind manufacturing efficiency).

3.3. Mass customization demand fulfillment

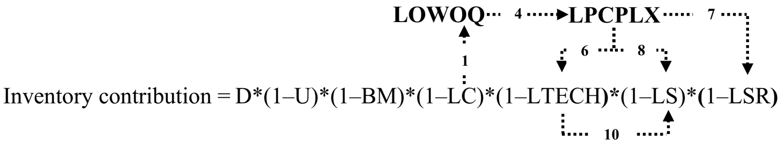
Based on the relationships established in Figure 2, we propose to re-write Equations 1 and 2 to reflect the performance of a manufacturing organization working in a mass customization environment, in terms of demand fulfillment (see Equations 3 and 4). For this matter:

- Standardization **S** becomes Customization **LC**, understood as the total number of manufacturing operations required to obtain a certain finished item (#O).
- Flexibility **F** becomes System´s reconfiguration **LSR**, understood as the total number of optional manufacturing routes that can be used in the process of building a finished item (#R).
- The elements Technification **LTECH** (understood as the total number of manufacturing operations a certain workcenter can perform, #OM) and Labor Skills **LS** (understood as the total number of workcenter manufacturing operations a single operator can handle, #S) are added. The inclusion of the **LTECH** and **LS** elements is supported by relationships 1, 4, 6, 7, 8, and 10 (see dotted lines in Equations 3 and 4).



Inventory-oriented level strategy		Capacity-oriented chase strategy	
Combination nomenclature	% of the highest missed demand achieved	Combination nomenclature	% of the highest missed demand achieved
345	54.5	1356	21.09
4	31.0	136	19.87
56	10.0	13	19.78
456	10.0	135	19.04
0	5.8	**13456**	18.45
35	5.5	1346	17.46
6	5.0	134	16.84
46	5.0	1345	16.03
5	4.5	1456	0.42
45	4.5	156	0.37
36	4.0	14	0.30
346	4.0	1	0.24
356	3.9	146	0.24
3456	3.9	15	0.21
3	3.6	145	0.21
34	3.6	16	0.18

(3)



Inventory contribution = D*(1–U)*(1–BM)*(1–LC)*(1–LTECH)*(1–LS)*(1–LSR)

(4)

According to the structure of Equations 3 and 4, the following should be expected:

- In a manufacturing scenario with demand uncertainty **U**= 0, a high level of demand fulfillment can be achieved if an inventory-oriented level strategy is followed (Figure 3), as long as **LC** = **LTECH** = **LS** = **LSR** = 0. That is, a manufacturing scenario where the total number of required manufacturing operations, workcenter manufacturing operations, workcenter manufacturing operations to be handled, and optional manufacturing routes is small.

- In a manufacturing scenario with demand uncertainty **U**= 1, a high level of demand fulfillment can be achieved if a capacity-oriented chase strategy is followed (Figure 4), as long as **LC** = **LTECH** = **LS** = **LSR** = 1. That is, a manufacturing scenario where the total number of required manufacturing operations, workcenter manufacturing operations, workcenter manufacturing operations to be handled, and optional manufacturing routes is large.

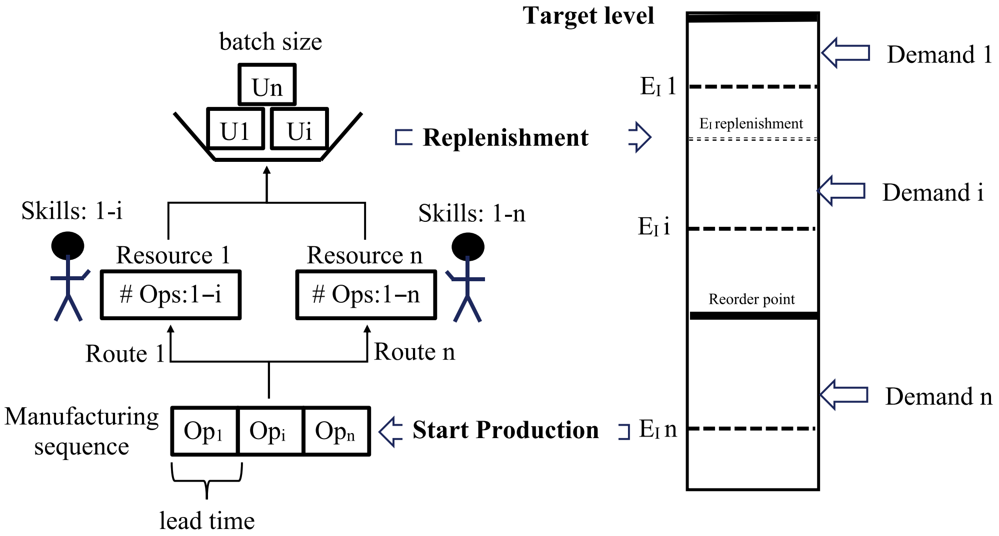


Figure 3. Inventory-oriented level strategy (Source: author constructed).

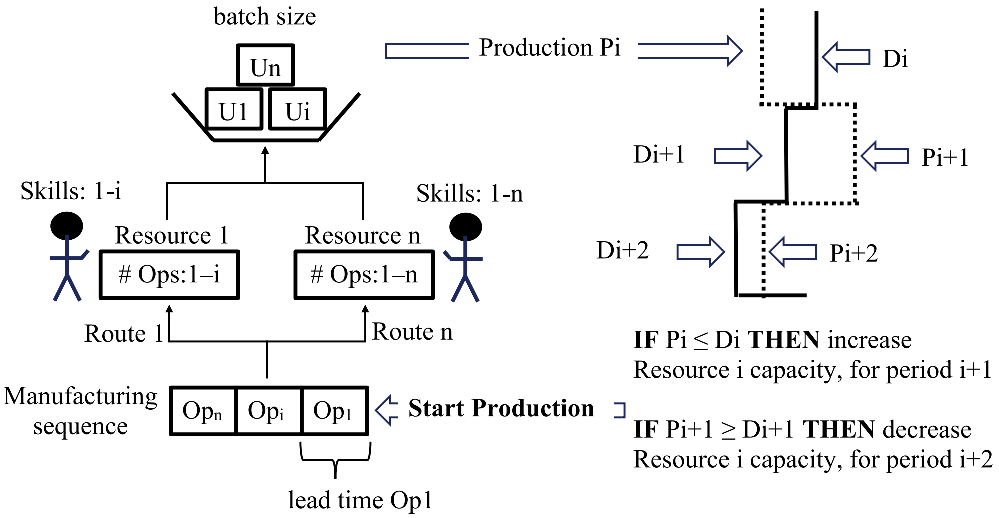


Figure 4. Capacity-oriented chase strategy (Source: author constructed).

Now, the inventory-oriented level strategy (Figure 3) can be explained as follows:

(1) Customer orders with a varying degree of demand quantity, arrive periodically.

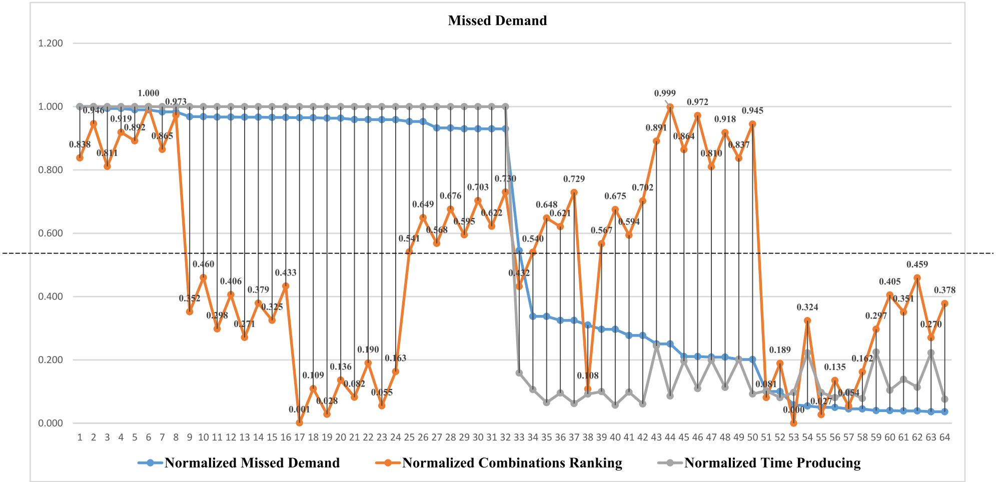


Figure 5. Normalized DES results: inventory-oriented level strategy.

(2) If the arriving customer order quantity ≤ current inventory level, then the Customer order is fulfilled immediately, and the inventory level is adjusted accordingly, i.e. new inventory level = old inventory level – customer order quantity.
(3) If the new inventory level ≤ reorder point level, then the production process is activated:

(a) The current inventory level is replenished with the output of the production process, in the amount equal to batch size.
(b) The production process stops when the current inventory level ≥ target level.

(4) If the customer order quantity ≥ current inventory level, then the customer order is partially fulfilled, and the total amount lost (of unfulfilled customer order) is increased accordingly, i.e. new amount lost = old amount lost + unfulfilled customer order.

and the capacity-oriented chase strategy (Figure 4) can be explained as follows:

(1) Customer orders with a varying degree of demand quantity, arrive periodically.
(2) The production process is activated and the customer order is fulfilled in a batch-size to batch-size basis, until the next customer order arrives.
(3) If by the time the next customer order arrives, the produced amount of units (provided by the production process) ≥ current customer order quantity, then:
    (a) The production process stops.
    (b) The current level of production capacity is decreased, i.e. the current number of manufacturing resources is decreased by one.
(4) If by the time the next customer order arrives, the produced amount of units (provided by the production process) ≤ current customer order quantity, then:

(a) The customer order is partially fulfilled, and the total amount lost (of unfulfilled Customer order) is increased accordingly, i.e. new amount Lost = old amount lost + unfulfilled customer order.
(b) The current level of production capacity is increased, i.e. the current number of manufacturing resources is increased by one.
(c) The production process starts fulfilling the new customer order.

For both strategies, each incoming customer order arrives periodically and has a varying demand size quantity; each unit composing the demand size quantity is assigned the same number of manufacturing operations; each manufacturing operation is assigned the same processing time (lead time). For both strategies, the production process consists of the following features:

- A unit composing the demand size quantity can follow a number of optional manufacturing routes.
- Each optional manufacturing route has a workcenter that can perform several different manufacturing operations:
  - In the case the total number of manufacturing operations to be performed (in a single unit composing the demand size quantity) ≥ the total number of manufacturing operations the workcenter can perform, then that unit must leave the workcenter and wait in line to re-enter it, to complete the remain of the manufacturing operations
- Each workcenter has an operator associated to it, that can handle several different workcenter manufacturing operations:
  - In the case the total number of workcenter manufacturing operations that can be handled by the associated operator ≤ the total number of manufacturing operations the workcenter can perform, then a new operator must be appointed to the workcenter.

3.4. Simulation model of the demand fulfillment strategies

The usefulness of Equations 3 and 4, to reflect the performance of a manufacturing organization working in a mass customization environment (in terms of demand fulfillment), is tested via a discrete-event simulation (DES) model of both the inventory-oriented level and capacity-oriented chase strategies. A justification for following a DES approach is presented in Appendix C, as well as an excerpt of the DES model developed for the inventory-oriented level strategy (Figure C1). The DES model was developed in ARENA (Kellton et al., 2004) and used to generate statistical output regarding the performance of each strategy. The following operational conditions were used:

- Each incoming customer order arrives periodically (every 15 minutes).
- Each incoming customer order is assigned with a demand size quantity, according to a normal distribution (with a mean and a standard deviation parameters).
- Each unit composing the demand size quantity, is assigned the same number of manufacturing operations, according to a uniform distribution (with a min and max parameters).

- Each manufacturing operation is assigned the same processing lead time.
- The production process is assumed to be operating continuously, i.e. breakdowns, changeover, setup, and load/unload times are assumed to be negligible.
- All the workcenters can process only one unit (of the demand size quantity) at a time and have a constant processing lead time.
- A simulation run time of 1,440 minutes (one day) was used.

The simulation run output was examined for reasonableness, according to the verification and validation approach suggested by Hwarng et al. (2005). Thirty replications were used for each scenario, in order to avoid significant variation in the observed results. Confidence intervals of 90% were used in order to provide the proper statistical basis for making inferences and conclusions. Sixtyfour different combinations were tested under these operative conditions (Table 3). These combinations are the result of varying the elements at two different variation levels (note: in the case of normally distributed values, they have parameters **μ** and **σ**, and are expressed as N(**μ,σ**). In the case of uniformly distributed, they have parameters **a** and **b**, and are expressed as U(**a,b**):

Table 3. Tested combinations (a cell highlighted in gray refers to the use of a high variation value).

Combination nomenclature	500	250	100	50	25	1	Combination numeric value	Combination nomenclature	500	250	100	50	25	1	Combination numeric value
0	1	3	4	5	6	7	0	345	1	3	4	5	6	7	400
1	1	3	4	5	6	7	500	346	1	3	4	5	6	7	375
3	1	3	4	5	6	7	250	347	1	3	4	5	6	7	351
4	1	3	4	5	6	7	100	356	1	3	4	5	6	7	325
5	1	3	4	5	6	7	50	357	1	3	4	5	6	7	301
6	1	3	4	5	6	7	25	367	1	3	4	5	6	7	276
7	1	3	4	5	6	7	1	456	1	3	4	5	6	7	175
13	1	3	4	5	6	7	750	457	1	3	4	5	6	7	151
14	1	3	4	5	6	7	600	467	1	3	4	5	6	7	126
15	1	3	4	5	6	7	550	567	1	3	4	5	6	7	76
16	1	3	4	5	6	7	525	1345	1	3	4	5	6	7	900
17	1	3	4	5	6	7	501	1346	1	3	4	5	6	7	875
34	1	3	4	5	6	7	350	1347	1	3	4	5	6	7	851
35	1	3	4	5	6	7	300	1356	1	3	4	5	6	7	825
36	1	3	4	5	6	7	275	1357	1	3	4	5	6	7	801
37	1	3	4	5	6	7	251	1367	1	3	4	5	6	7	776
45	1	3	4	5	6	7	150	1456	1	3	4	5	6	7	675
46	1	3	4	5	6	7	125	1457	1	3	4	5	6	7	651
47	1	3	4	5	6	7	101	1467	1	3	4	5	6	7	626
56	1	3	4	5	6	7	75	1567	1	3	4	5	6	7	576
57	1	3	4	5	6	7	51	3456	1	3	4	5	6	7	425
67	1	3	4	5	6	7	26	3457	1	3	4	5	6	7	401
134	1	3	4	5	6	7	850	3467	1	3	4	5	6	7	376
135	1	3	4	5	6	7	800	3567	1	3	4	5	6	7	326
136	1	3	4	5	6	7	775	4567	1	3	4	5	6	7	176
137	1	3	4	5	6	7	751	13,456	1	3	4	5	6	7	925
145	1	3	4	5	6	7	650	13,457	1	3	4	5	6	7	901
146	1	3	4	5	6	7	625	13,467	1	3	4	5	6	7	876
147	1	3	4	5	6	7	601	13,567	1	3	4	5	6	7	826
156	1	3	4	5	6	7	575	14,567	1	3	4	5	6	7	676
157	1	3	4	5	6	7	551	34,567	1	3	4	5	6	7	426
167	1	3	4	5	6	7	526	134,567	1	3	4	5	6	7	926

- Demand uncertainty (1.- U). High variation values, U = N(50, 25); low variation values, U = N(50, 2.5).
- Number of operations LC (3.- #O). High variation values, #O = U(4,6); low variation values, #O = U(1,3).
- Number of routes LSR (4.- #R). High variation values, #R = 2; low variation values, #R = 1.
- Number of workcenter operations LTECH (5.- #OM). High variation values, #OM = U(4,6); low variation values, #OM = U(1,3).
- Number of workcenter operations able to be handled by an operator LS (6.- #S). High variation values, #S = U(4,6); low variation values, #S = U(1,3).
- Processing lead time (7.- LT). High variation values, LT = 1.0; low variation values, LT = 0.1.

Each combination is identified with a nomenclature that identifies which of those elements were varied at the same time, i.e. combination 37 refers to a combination where elements 3 and 7 were varied. Moreover, each combination is assigned with a numeric value so it can be ranked later on, and associated to the results obtained from the DES.

4. Scenario results and analysis

4.1. The inventory-oriented level and capacity-oriented chase strategies

Table 4 shows the simulation results of the sixty four tested combinations under the inventory-oriented level strategy, while Table 5 do the proper for the capacity-oriented chase strategy. In both cases, the missed demand values are sorted from largest to smallest value, where a high value of missed demand – defined as the total amount lost demand due to unfulfilled customer orders – is the result of a low level of demand fulfillment. Moreover, for the case of Table 4, 'time producing' refers to the amount of time the production process is activated, while for Table 5, 'workload' refers to the amount of work needed to be performed, that is, #O * LT. On the other hand, Figures 5 and 6 presents the normalized values of Tables 5 and 6, respectively. In both cases, all the values above the dotted line correspond to combinations with a high U, #O, #R, #OM, and #S (or UOROMS) values.

Now, the premise behind Equation 3 is that an inventory-oriented level strategy allows the achievement of a high level of demand fulfillment, for a manufacturing scenario with low UOROMS values. In the case of Equation 4, the premise is that a capacity-oriented chase strategy allows the achievement of a high level of demand fulfillment, for a manufacturing scenario with high UOROMS values. However, for both premises, there is a set of combinations that do not comply with them (Table 6).

An analysis of Table 6 reveals the following:

- Regarding Equations 3 and 4; high missed demand values are always obtained when there are high LT values, and low missed demand values are always obtained when there are low LT values. This means that the role of the LT must be incorporated into the structure of Equations 3 and 4, as in their current form, they fail to reflect these results (Equations 3′and 4', expressed in terms of UOROMS).

Table 4. DES results: inventory-oriented level strategy.

Combination nomenclature	Missed Demand	Combination numeric value	Time Producing	Combination nomenclature	Missed Demand	Combination numeric value	Time Producing
1367	1040.2500	776	1440.0000	345	567.32	400	228.7
13,467	1040.2500	876	1440.0000	1	351.0200	500	153.0600
137	1034.29	751	1440.0000	14	351.0200	600	93.56
1347	1034.29	851	1440.0000	156	337.85	575	137.65
13,567	1029.7400	826	1440.0000	1456	337.8500	675	89.5250
134,567	1029.7400	926	1440.0000	4	322.5600	100	132.5900
1357	1022.9400	801	1440.0000	16	308.4600	525	143.83
13,457	1022.9400	901	1440.0000	146	308.46	625	82.1717
3567	1007.2700	326	1440.0000	15	288.4400	550	141.64
34,567	1007.2700	426	1440.0000	145	288.44	650	87.6739
367	1005.99	276	1440.0000	1356	260.6600	825	351.7500
3467	1005.9900	376	1440.0000	13,456	260.6600	925	123.6400
37	1005.7000	251	1440.0000	135	219.13	800	282.22
347	1005.7	351	1440.0000	1345	219.1300	900	157.54
357	1004.71	301	1440.0000	13	217.2500	750	286.78
3457	1004.7100	401	1440.0000	134	217.25	850	163.06
7	1003.9100	1	1440.0000	136	209.38	775	291
47	1003.9100	101	1440.0000	1346	209.38	875	133.06
67	1002.3000	26	1440.0000	56	104.1800	75	147.75
467	1002.3	126	1440.0000	456	104.18	175	116.57
567	997.8	76	1440.0000	0	60.3260	0	140.3200
4567	997.8000	176	1440.0000	35	56.7303	300	319.98
57	997.4800	51	1440.0000	6	52.0558	25	139.6500
457	997.48	151	1440.0000	46	52.0558	125	116.55
17	991.2400	501	1440.0000	5	47.0053	50	142.0100
147	991.24	601	1440.0000	45	47.0053	150	112.69
167	970.3	526	1440.0000	36	41.4192	275	323.50
1467	970.3000	626	1440.0000	346	41.4192	375	150.1
157	967.44	551	1440.0000	356	40.4525	325	199.43
1457	967.4400	651	1440.0000	3456	40.4525	425	163.7600
1567	967.2900	576	1440.0000	3	37.7358	250	320.3200
14,567	967.2900	676	1440.0000	34	37.7358	350	109.19

Inventory contribution $= D*(1-U)*(1-BM)*(1-\#O)*(1-\#OM)*(1-\#S)*(1-\#R)*(1-LT)$ (3')

Capacity contribution $= D*U*BM*\#O*\#OM*\#S*\#R*(1-LT)$ (4')

- Regarding Equation 3; within the combinations not complying with the premise of Equation 3:
  - high #O (↑#O) values lead to increase the level of missed demand, in the presence of low U, high LT values.
  - high #O (↑#O) values lead to decrease the level of missed demand, in the presence of high U, low LT values.
  - high #R (↑#R) values lead to decrease the level of missed demand, always.

These findings can be expressed by the following expression (see, Table 7):
$[(1-U)*(1-\#O)*(LT)+(U)*(\#O)*(1-LT)]$

- Regarding Equation 4; within the combinations not complying with the premise of Equation 4:

Table 5. DES results: capacity-oriented chase strategy.

Combination numeric value	Missed Demand	Combination numeric value	Workload	Combination nomenclature	Missed Demand	Combination numeric value	Workload
13,467	506.9800	876	247.0000	1356	106.9700	825	25.3724
1347	497.9000	851	251.1300	136	100.7500	775	24.8271
13,457	493.7300	901	249.3700	13	100.3300	750	24.9259
134,567	493.5800	926	250.6700	135	96.5500	800	24.1635
34,567	486.4500	426	250.1100	13,456	93.5667	925	25.3122
3457	485.7800	401	251.3400	1346	88.5333	875	25.0084
347	482.5700	351	250.3000	134	85.3833	850	24.7598
3467	482.5300	376	249.4800	1345	81.3167	900	24.7484
137	442.6800	751	249.6100	35	5.0167	300	25.0052
37	432.1700	251	249.7300	356	4.8333	325	24.9433
357	431.0300	301	248.8100	3456	4.7333	425	25.0165
3567	429.0200	326	250.5900	345	4.4833	400	24.8834
13,567	428.2500	826	250.8500	36	4.3833	275	24.9846
17	428.2500	501	250.8500	346	4.3000	375	24.7857
1357	425.8800	801	253.2000	3	4.2000	250	25.0670
157	425.8800	551	253.2000	34	4.1667	350	25.0225
367	421.5000	276	249.4900	1456	2.1333	675	10.1655
1367	420.7300	776	241.8800	156	1.9167	575	9.9383
1567	417.5000	576	104.3300	14	1.5667	600	10.1520
167	416.9000	526	100.3900	1	1.2667	500	10.0282
57	377.3700	51	100.8600	146	1.2500	625	10.1803
147	375.8500	601	101.8300	15	1.1000	550	9.8759
1467	375.2700	626	101.9200	145	1.1000	650	9.8905
7	375.0300	1	100.1500	16	0.9500	525	10.0398
567	373.8200	76	100.4400	0	0.0000	0	10.0820
1457	372.4800	651	99.3600	4	0.0000	100	10.0820
67	365.0200	26	99.2000	5	0.0000	50	9.8478
14,567	364.9200	676	100.3200	6	0.0000	25	10.0390
4567	295.9000	176	100.6500	45	0.0000	150	9.8478
47	294.3700	101	101.1900	46	0.0000	125	10.0390
467	289.9000	126	99.1500	56	0.0000	75	10.0730
457	286.6200	151	98.3762	456	0.0000	175	10.0730

- high #O (↑#O) values lead to increase the level of missed demand always, independently of the LT level of variation.
- high #R (↑#R) values lead to decrease the level of missed demand, most of the time.

This finding can be expressed by the following expression (see, Table 7):
[(U)*(1 – #O)*(LT) + (1 – U)*(#O)*(1 – LT)]

4.2. Managerial implications

According to the premises behind Equations 3 and 4, the theoretically lowest missed demand values should be obtained at combination **0** (for the Inventory-oriented level strategy), and at combination **13,456** (for the capacity-oriented chase strategy). However, this is not the case. When those combinations not complying with the premises of Equations 3 and 4 (Table 6), are taken out from Tables 4 and 5, and we focus only on the ‘low LT values’ side of these Tables – that is, where the low missed demand values are

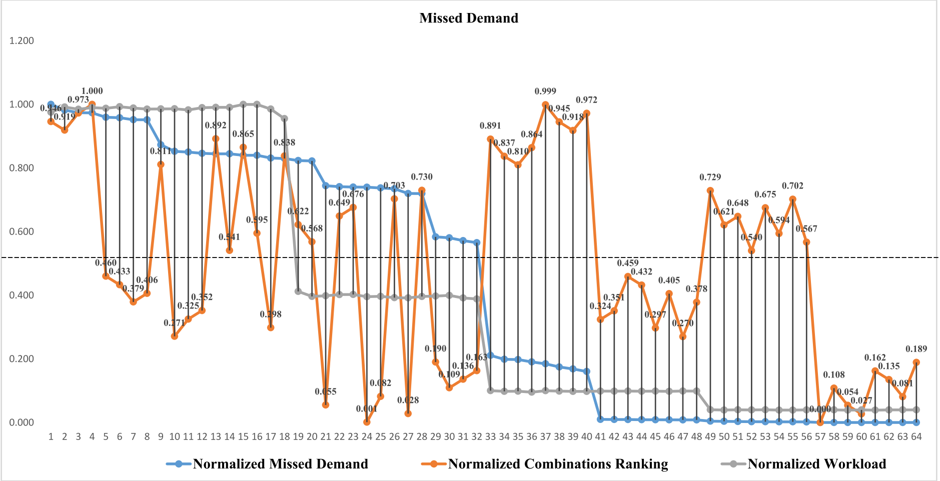


Figure 6. Normalized DES results: capacity-oriented chase strategy.

Table 6. Combinations not complying with the premises of Equations 3 and 4.

Combinations not complying with the premise of . . .			
Equation 3		Equation 4	
Low UROMS values leading to high missed demand values	High UROMS values leading to low missed demand	High UROMS values leading to high missed demand values	Low UOROMS values leading to low missed demand values
Combination nomenclature		Combination nomenclature	
3567	1	13,467	35
34,567	14	1347	356
367	156	13,457	3456
3467	1456	134,567	345
37	16	137	36
347	146	13,567	346
357	15	17	3
3457	145	1357	34
7	1356	157	0
47	13,456	1367	4
67	135	1567	5
467	1345	167	6
567	13	147	45
4567	134	1467	46
57	136	1457	56
457	1346	14,567	456
High LT values	Low LT values	High LT values	Low LT values

obtained – we obtain Table 8. For both strategies, there are eleven combinations that offer lower missed demand values than the theoretically lowest missed demand values. A closer look to these results reveals that:

Table 7. Findings from Table 6 results.

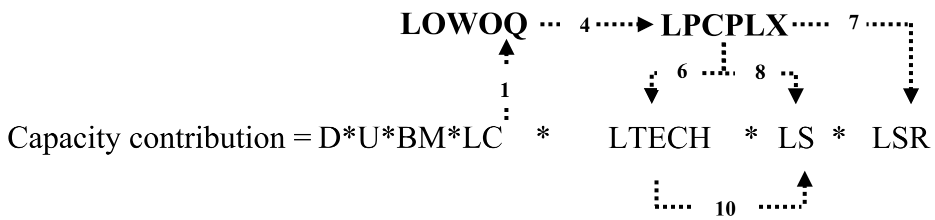
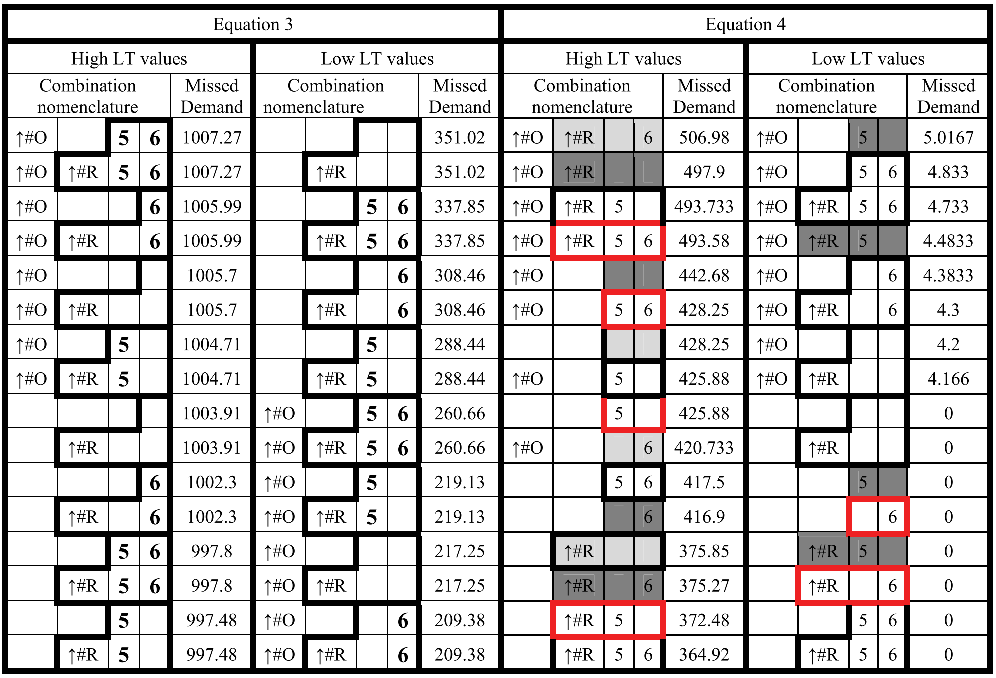


Table 8. Conditions for lower than theoretically lowest missed demand values.



Equation 3										Equation 4									
High LT values					Low LT values					High LT values					Low LT values				
Combination nomenclature				Missed Demand	Combination nomenclature				Missed Demand	Combination nomenclature				Missed Demand	Combination nomenclature				Missed Demand
↑#O		5	6	1007.27					351.02	↑#O	↑#R		6	506.98	↑#O		5		5.0167
↑#O	↑#R	5	6	1007.27		↑#R			351.02	↑#O	↑#R			497.9	↑#O		5	6	4.833
↑#O			6	1005.99			5	6	337.85	↑#O	↑#R	5		493.733	↑#O	↑#R	5	6	4.733
↑#O	↑#R		6	1005.99		↑#R	5	6	337.85	↑#O	↑#R	5	6	493.58	↑#O	↑#R	5		4.4833
↑#O				1005.7				6	308.46	↑#O				442.68	↑#O			6	4.3833
↑#O	↑#R			1005.7		↑#R		6	308.46	↑#O		5	6	428.25	↑#O	↑#R		6	4.3
↑#O		5		1004.71			5		288.44					428.25	↑#O				4.2
↑#O	↑#R	5		1004.71		↑#R	5		288.44	↑#O		5		425.88	↑#O	↑#R			4.166
				1003.91	↑#O		5	6	260.66			5		425.88					0
	↑#R			1003.91	↑#O	↑#R	5	6	260.66	↑#O			6	420.733		↑#R			0
			6	1002.3	↑#O		5		219.13			5	6	417.5			5		0
	↑#R		6	1002.3	↑#O	↑#R	5		219.13				6	416.9				6	0
		5	6	997.8	↑#O				217.25		↑#R			375.85		↑#R	5		0
	↑#R	5	6	997.8	↑#O	↑#R			217.25		↑#R		6	375.27		↑#R		6	0
		5		997.48	↑#O			6	209.38		↑#R	5		372.48			5	6	0
	↑#R	5		997.48	↑#O	↑#R		6	209.38		↑#R	5	6	364.92		↑#R	5	6	0

- Those conditions that contribute to lower missed demand values, for the case of the capacity-oriented chase strategy, are the same that contribute to higher missed demand values (red lines), for the case of the inventory-oriented level strategy. The opposite situation presents the same results (black lines).
- For both strategies; the #R (number of routes), #OM (number of workcenter operations), and #S (number of workcenter operations able to be handled by an operator), appears almost equally distributed within these eleven combinations.

According to Andersen et al. (2017), a critical enabler for an efficient mass customization production system is its process flexibility, so, the findings presented in Table 8 can be understood from this perspective. In the words of Peng et al. (2008), process flexibility is a bundle of routines and resources that contribute to performance improvement.

Moreover, they allow the production system to adapt to diverse customer requirements, a necessary condition mentioned by Blecker and Friedrich (2007) and Dhungana et al. (2017). From this point of view, the number of routes #R, workcenter operations #OM, and workcenter operations able to be handled by an operator #S, contribute to process flexibility, as they allow to produce ‘more with less’ (through several different combinations), precisely the core concept behind manufacturing efficiency. However, even though, increasing the level of flexibility of the mass customization production system brings an improvement of manufacturing efficiency (in the form of low missed demand values), it also comes with some drawbacks:

(1) It is a fact that the higher flexibility a system has, the more difficult it is to achieve high efficiency, due to the increasing level of system’s complexity (Gullander et al.,). This translates into longer waiting times and queue lengths (at each workcenter), something that in turn affects the ability to perform a robust resources scheduling, and with this, the desired manufacturing efficiency (Martínez-Olvera et al., 2016).
(2) Within a highly flexible production environment, typical of an Industry 4.0 context, the sequence of manufacturing steps necessary to build a customized product, cannot longer be pre-defined, as the product’s value creation chain has to be created ad hoc. This makes hard to performing the energy consumption what-if analyses required by a serious Sustainability analysis (2020).

Fortunately, the smart components of Industry 4.0 – namely, smart products and machines – can help reduce the complexity inherent to managing the mass customization production system (Kagermann et al., 2013), via the use of information technologies (Boer et al., 2017), as long as there is no lack of information quality and availability for the use of these associated technologies (Graefenstein et al.,). Also, a set of entropy-based formulations has been developed as an alternative way of performing the initial steps of the energy consumption what-if analyses (2020). Summarizing: in order to truly benefit from the flexibility provided by the #R, #OM, and #S elements, it becomes necessary to provide the mass customization production system with the ‘smart’ element, which is precisely the idea behind of the SMC4.0 mentioned in section 2.3.

5. Conclusions and future research

The central idea behind the Industry 4.0 paradigm is the implementation of a fully automated and digitalized production environment, which is directly related to the mass customization concept, and that has clear sustainability implications. This has forced manufacturing enterprises to find new ways to produce ‘more with less’, through the use of energy-efficient manufacturing processes. In this research effort, we considered that the first step to be taken towards this goal is to quantify the ability of a manufacturing organization to produce ‘more with less’ (for the case of a mass customization environment), so manufacturing efficiency can be expressed within a sustainability context. The original contributions of this paper are a CLD that define a mass customization environment, and the demand fulfillment analytical expressions, for the case of a mass customization environment. The usefulness of the analytical expressions were put to the test via a DES model of two different demand fulfillment strategies (namely inventory-oriented level and capacity-oriented chase strategies). From the obtained results, several conclusions can be derived:

1.- The analytical expressions act as a fairly good trend indicator of the missed demand values increase/decrease. The analytical expressions fail to act as estimator of the missed demand final values.

2.- The accuracy of the expression – regarding how close it follows the missed demand behavior (that is, the values increase/decrease) – is related to the role played by the LT. The missed demand behavior (that is, the values increase/decrease) is affected by the flexibility of the manufacturing process.

Based on these findings, some of the recommendations for future research include:

1.- To introduce a methodology to perform 'what-if' scenario analysis, that could guide the process of finding the best alternative, regarding the achievement of high levels of demand fulfillment. The entropy-based (entropic) formulation presented in 2020, have probed to be a fairly good trend indicator of the increase/decrease performance parameters (i.e. queue length and waiting times) of a mass customization production system operating within an Industry 4.0 context. The structure of the entropic formulation can be modified to include the number of routes, workcenter operations, and workcenter operations able to be handled by an operator (as in its current form, it only reflects the number of operations) and to act as a good trend indicator of the increase/decrease demand fulfillment ability.

2.- To explore the impact of the smart components of Industry 4.0 in the achievement of high levels of demand fulfillment, and the inclusion of them into the structure of the analytical expressions. These smart components refer to smart products and smart machines, which 'orchestrate the required resources and negotiate the next step' to complete the production processes). The challenge is to include this 'social' way of working into the demand fulfillment analysis. Regarding this point, some of the initiatives mentioned in Appendix C could be used as the starting point of this new research effort.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data Availability

The DES model used to support the findings of this study is available from the corresponding author upon request.

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Appendix A

After reading 75 selected articles and applying the ProKnow-C method, Helmann et al. (2020) identified six architectures that could be used to develop an intelligent manufacturing solution and promote systematic standardization within Industry 4.0/smart manufacturing:

- Reference Architecture Model Industrie 4.0 (RAMI 4.0); within this proposal, there are six-layers of integration responsible for making this relationship between all components of the architecture: Business, Functional, Information, Communications, Integration, and Asset layers.
- The Industrial Internet Reference Architecture (IIRA); within this proposal, there are five-layers to describe the functions in an industrial system, their interrelation, structure, and interactions: Business, Application, Information, Operations, and Control layers.
- IBM Industry 4.0 Architecture (IBM); within this proposal, there are three levels: Edge, Plant/factory/shop floor, and Enterprise or back-end levels.
- Smart Manufacturing Ecosystem (SME); within this proposal, there are four dimensions: Product, Production, Business, and Manufacturing dimensions.
- Intelligent Manufacturing System Architecture (IMSA); within this proposal, three-dimensions are observed: Intelligent functions, Lifecycle, and System levels.
- Industrial Value Chain Reference Architecture (IVRA); within this proposal, three views are observed: Asset, Activity, and Management views.

Finally, the Object Management Group proposes the Industrial Internet Reference Architecture, which proposes four views: Business, Usage, Functional, and Implementation viewpoints. As the reader can observe, all of these proposals have elements in common, so right now, it is too early to call one of them as the dominant over the others. The reader is invited to review the details of each proposal and determine which one fits better to their particular interests.

Table B1. Mass customization CLD relationships, explanation (Source: Author Constructed).

Structural elements		Among-alignment conditions				Logic behind within-alignment conditions	
	CUSTOMER	PRODUCT	PROCESS	RESOURCE			
Within-alignment conditions	BUSINESS	Customization	X	2Production variety, 3,11Production volume	X	Customization determines the Production volume and the Production variety, i.e. an standard product allows the manufacturing system the production of high volumes, as it has to deal with only a small number of models.	
	MANUFACTURING	X	4Product's complexity	7System's reconfiguration	6Technification, 8,10Labor skill	Product's complexity conditions the System's reconfiguration, Technification, and Labor skills, i.e. the manufacturing of a product with a few operations that are easy to execute, is better handed by a hard-connected workstations/rigid flow manufacturing system, that uses specialized-use equipment operated by single-task specialist.	
	MARKETING	1OW/OQ*	4Product's complexity	X	5,9Components	OW/OQ determines Product's complexity and the Components; i.e. a product with features that are common to similar products offered in the market, is built with a few operations that are easy to execute, and using a small number of manufacturing components.	

(*Continued*)

Table B1. (Continued).

Structural elements	Among-alignment conditions			Logic behind within-alignment conditions	
CUSTOMER	PRODUCT	PROCESS	RESOURCE		
Logic behind among-alignment conditions	Customization determines the OW/OQ; i.e. an standard product consists mainly of a product with features that are common to similar products offered in the market.	Product's complexity; i.e. a product with a few operations that are easy to execute.	Production volume depends on the Production variety and the System's reconfiguration; i.e. producing high volumes of a product is only possible when there is only a small number of models, and they are produced using a hard-connected workstations/rigid flow manufacturing system.	Technification affects the Labor skills and determines then Components i.e. the running of specialized-use equipment requires the involvement of single-task specialist, and the handling of a small number of manufacturing components.	* Order Winners (OW), unique features found only in the offered product; Order Qualifiers (OQ), common features found in similar products offered in the market.

Appendix B

Table B2. Mass customization CLD relationships, system dynamics (SD) model equations (Source: author constructed).

	Range of values	
Mass Customization structural elements	0	1
Level of customization (lc)	Standard product	Personalized product
Level of OW/OQ (lowoq)	100% Common features	100% unique features
Level of product's complexity (lpcplx)	Few operations/easy to execute	Lot of operations/hard to execute
Level of production variety (lpva)	A small number of product models	A large number of product models
Level of production volume (lpvo)	A few units produced	A lot of units produced
Level of system's reconfiguration (lsr)	Hard-connected workstations/ rigid flow	Loose-connected workstations/ flexible flow
Level of equipment technification (ltech)	Specialized-use equipment	General-use equipment
Level of labor skill (ls)	Single-task specialist	Multiple-task generalist
Level of components (lcomp)	Small number of components	Large number of components

Rn*	From	To	Rt**	Formula	The maximum amount of different …
1	lc	lowoq	+	lowoq = lc * BoFeatures	BoFeatures … features a product can have.
2	lc	lpva	+	lpva = lc * Catalog	Catalog … products a manufacturing system can produce.
3	lpva	lpvo	-	lpvo = (1–lpva) * Throughput	Throughput … production volume a manufacturing system can achieve.
4	lowoq	lpcplx	+	lpcplx = lowoq * BoOp	BoOp … operations a manufacturing system can perform
5	lowoq	lcomp	+	lcomp = lowoq * BoM	BoM … product's components that can be handled by the manufacturing equipment
6	lpcplx	ltech	+	ltech = lpcplx * BoEqOp	BoEqOp … operations a manufacturing equipment can perform.
7	lpcplx	lsr	+	lsr = lpcplx * BoRoutes	BoRoutes … routes a manufacturing system can offer.
8	lpcplx	ls	+	ls = lpcplx * BoTasks	BoTasks … tasks a manufacturing operator must perform.
9	ltech	lcomp	+	lcomp = ltech * BoM	BoM … product's components that can be handled by the manufacturing equipment
10	ltech	ls	+	ls = ltech * BoTasks	BoTasks … tasks a manufacturing operator can perform.
11	lsr	lpvo	-	lpvo = (1-lsr) * Throughput	Throughput … production volume a manufacturing system can achieve.

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

Appendix C

As explained in Section 1, the main difference between the mass customization and the mass individualization paradigm, is the role played by the customer into the design of the final product. Due to the of open source/architecture nature of the mass personalized products, the level of manufacturing interconnection required results in a set of crowded, clustered, and decentralized characteristics (Leng & Jiang, 2018). In order to address this 'social' way of working, some initiatives have been proposed: Open Production, (Wulfsberg et al., 2011); Peer Production (Kostakis & Papachristou, 2014); Crowd-Manufacturing (Bonvoisin & Boujut, 2015); Maker Manufacturing (Johar et al.,); crowdsourcing-driven/community-based social manufacturing (Jiang et al., 2016). Now, in order to reflect the performance of this 'social' way of working, special approaches are needed. Without claiming this to be an extensive cover of them (as this falls out of the main topic of this paper), we can identify three main approaches:

1) Holistic; like the one proposed by Leng and Jiang (2019a), where a model of the of discrete manufacturing system dealing with the mass customization paradigm is built, and coupled with the radio frequency identification (RFID) technology, that in this case, is used for performance tracking – at different levels of abstraction – of the elements composing the manufacturing system.

2) Decentralized self-organizing; like the one proposed by Leng et al. (2019b), where a decentralized blockchain-driven model is presented to track the authenticity and quality of the co-created, personalized, open architecture products.

3) Hybrid; like the one proposed by Leng et al. (2020), where a a permissioned blockchain-driven IIoT (Industrial Internet of Things) model can enable partially decentralized self-organization.

As we are addressing the mass customization paradigm, which does not require such a high degree of customer involvement as the mas personalization paradigm, in this paper we followed an approach similar to the one presented in Raza et al. (2018), where a discrete-event simulation (DES) model of a mass customization production system was built to study the impact of introducing the Industry 4.0 paradigm.

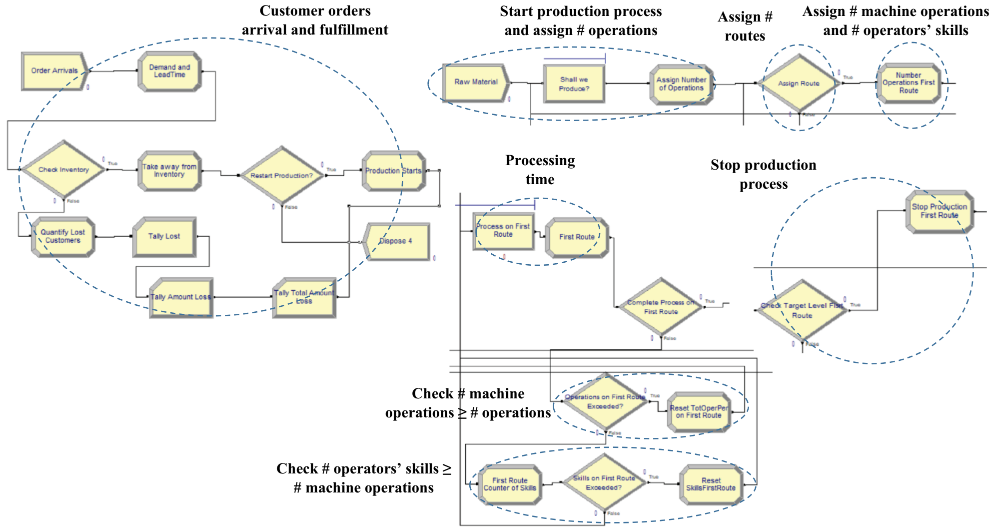

Figure C1. Inventory-oriented level strategy, excerpt of the DES model (Source: Author Constructed).