

Research Article

An Entropy-Based Formulation for the Support of Sustainable Mass Customization 4.0

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Industry 4.0, an information and communication umbrella of terms that includes the Internet of Things (IoT) and cyber-physical systems, aims to ensure the future of the manufacturing industry competing in a proper environment of mass customization: demand for short delivery time, high quality, and small-lot products. Within this context of an Industry 4.0 mass customization environment, success depends on its sustainability, where the latter can only be achieved by the manufacturing efficiency of the smart factory-based Industry 4.0 transforming processes. Even though Industry 4.0 is associated with an optimal resource and energy productivity/efficiency, it becomes necessary to answer if the integration of Industry 4.0 elements (like CPS) has a favorable sustainability payoff. This requires performing energy consumption what-if analyses. The original contribution of this paper is the use of the entropy-based formulation as an alternative way of performing the initial steps of the energy consumption what-if analyses. The usefulness of the proposed approach is demonstrated by comparing the results of a discrete-event simulation model of mass customization 4.0 environment and the values obtained by using the entropy-based formulation. The obtained results suggest that the entropy-based formulation acts as a fairly good trend indicator of the system's performance parameters increase/decrease. The managerial implications of these findings are presented at the end of this document.

1. Introduction

The demand increase for a variety of short-delivery-time, high-quality, and small-lot products requires the use of innovative production approaches as the one proposed by Industry 4.0 paradigm, which combines manufacturing, automation, information, computing, communication, and control technologies—via the use of the Internet of Things (IoT), Big Data, and cyber-physical systems- (CPS-) associated technologies—in order to establish an interconnected industrial value creation process [1–3]. By bringing together the physical world, i.e., manufacturing processes, with the digital world, i.e., digital entities and procedures [4], each component in the manufacturing system is able to send and receive commands from other components via the Internet [5].

Now, even though Industry 4.0 is associated with an optimal resource and energy productivity/efficiency [6, 7], it becomes important to discuss the social/environmental impacts of the extensive IT infrastructure required to connect the physical and virtual worlds and consequences [1]. This makes it necessary to answer if the integration of Industry 4.0 elements (like CPS) has a favorable sustainability payoff, that is, a proper balance between the economic and environmental perspectives [8]. For this reason, the next section reviews the relationship between sustainability, Industry 4.0, value creation, and energy efficiency. Deriving from this literature review, we proceed to define the research features, that is, (1) to identify the research gaps and opportunities; (2) to enunciate the research proposal, (3) to establish the proposed research methodology; and (4) to highlight the research originality, usefulness, and contributions.

2. Literature Review

2.1. Smart Factory, Industry 4.0, and Sustainability. The study in [9] mentions four elements of value creation that, according to [10], can be characterized as the basis of a smart factory, namely, smart customers, products, processes, and resources [11]. In this sense, a smart factory is obtained when a CPS is coupled with a decentralized, self-contained execution and decision-making structure [12, 13], and a “self-conscious” environment is obtained [7]: smart products (products that request themselves the required resources to complete the production processes) and smart machines (machines can self-organize themselves to orchestrate the production processes), which together have the required knowledge to answer questions like “when was I made?”; “which parameters should be used to produce me?”; and “where should I be delivered to?”

On the other hand, the continued success of organizations is increasingly dependent on achieving the balance between three main types of responsibility, namely, economic, social, and environmental types [14], that is, the Triple Bottom Line (TBL) of sustainability. In this sense, Industry 4.0 has been often linked to sustainability, i.e., [15], mentioning sustainability as one of the three main requirements of CPS-based smart manufacturing systems—the other two being smart products and smart machines—when analyzing the Industry 4.0 paradigm. Some of the opportunities in Industry 4.0 for achieving sustainability are discussed in [16–18], while the sustainability implications of Industry 4.0 for organizations are reviewed in [19, 20]. Sustainability is mentioned in [15, 21] as one of the three main requirements of a CPS-based, smart manufacturing systems, as this latter would make it possible to achieve higher agility, productivity, and sustainability levels necessary to cope with global challenges, according to [22–25]. The importance of IoT and Big Data analytics in supply chain sustainability is highlighted in [26–29]. In the case of IoT, it promotes—besides innovation, customization, and knowledge sharing—sustainability in a global context [30, 31], and when in conjunction with Big Data it enables cleaner [32] and more sustainable production [28]. Finally, the use of a cloud platform by Industry 4.0 allows the intelligent management of shared resources and services, which in turn results in achievement of lower production costs and high levels of productivity and sustainability [32].

Regarding the use of discrete event simulation and sustainability, according to [33], simulation can be used to calculate unknown environmental quantities, and therefore discrete event simulations are a powerful method to assess the sustainability of new processes. The study in [34, 35] presents MILAN, a prototype of a sustainability-enhancing simulation software that allows accurate analysis of typically economic aspects and considers relevant environmental perspectives such as consumption of commodities and resources and additives, energy demand, waste accumulation, and emission generation. The study in [36] claims that modelling and simulation (M&S) techniques can provide helpful aid to TBL management, enabling the test of various TBL strategies [37]. According to [38], the TBL-based

discrete event simulation (DES) models developed for sustainability analysis have several limitations: they do not cover the whole TBL-based system, tend to ignore the interconnections with high-level and low-level operations, do not support proactive behavior (which is important when simulating social factors of TBL), and are mostly used at the operational level of abstraction rather than at strategic level.

2.2. Sustainability and Value Creation. A business model focuses on the “what” side of value creation, while a business process model (more detailed than the business model) focuses on the “how” side of value creation; it should be used as a starting point for the analysis of the value creation process and [39, 40] report that there is no qualitative assessment of the contribution of Industry 4.0 to sustainable value creation. In the best case, sustainability is considered a business feature of Industry 4.0 [41] and is considered to be one of the elements of its business model [42]. It has been stated that Industry 4.0 only tackles sustainability issue when its benefits also have an economic benefit [40], as it goes hand in hand with Industry 4.0’s revenue model [43]. For this reason, the sustainability issue and its link with Industry 4.0 has been discussed from a business modelling perspective by [16, 17]. Moreover, there is a need to develop innovative business models that guarantee sustainability [44]. In this sense, a business model ontology—describing the essential building blocks and their relationships—would make it easier for managers to design a sustainable business model [43]. A review of sustainable business models in Industry 4.0 is presented in [40], and the study in [18] identifies opportunities for Industry 4.0 which can result in sustainable business models. Finally, the authors of [40] propose a search agenda that includes the development of sustainable value propositions for Industry 4.0 and the development of cost-benefit analysis/revenue models for Industry 4.0 supporting sustainability.

Regarding the use of discrete event simulation and value creation, business process simulation can be split into long-term strategic planning and short-term operational planning [45]. Examples of long-term strategic planning are presented in [46, 47] and [48]. Papers on short-term operational planning started to appear since the millennium; that is, the study in [49] presents a simulation model using predefined process models enriched with probability distributions from event logs; in [50], the simulation model is built extracting both the process model and probability distributions from log files. A number of papers have been dedicated to business process modelling, for example, in [51], while the authors of [52] present a comparison of business process simulation tools, and the authors of [53] present a classification of the business processes modelling technologies and technologies, including the use of discrete event simulation.

2.3. Sustainability and Energy Efficiency. Energy-efficient manufacturing is an important aspect of sustainable development in current society [54]. According to [55], manufacturing enterprises have to find new ways to produce “more with less,” as the result from the pressure of customers

demanding for energy-efficient, eco-efficient manufacturing processes [56], where the core concept is to satisfy high quality, low cost, and low environmental impact simultaneously [57]. Within this context, three facts must be taken into account:

- (1) The value creation of a product is a manufacturing process chain necessary to transform the input material's form, shape, and/or properties into the output finished products, which in turn consumes energy—and other auxiliary resources—and induces environmental impacts [58].
- (2) An energy-efficiency analysis requires creating an energy consumption profile for each resource—involved at each step—of the whole manufacturing process chain [59].
- (3) The energy consumption of a resource is mostly related to the time spent in specific operative states [59].

Energy efficiency (or energy productivity) refers to producing the same amount of products in the right time, with the right quality consuming less energy [58, 60], in order to achieve the reduction of CO₂ emissions [61]. The study in [55] proposes an energy efficiency metric that compares the energy consumption with the corresponding output generated. In this metric, energy efficiency is strongly dependent on the process time (or operative states), even though only a small fraction of this latter actually adds value to the product. The study in [57, 58] extends the previous metric into an eco-efficiency index, which expresses the balance of the product value created by the process versus the cost and the environmental impact necessary to fabricate the product. The authors of [61] mention that it is required to convert the energy consumption into primary CO₂ emissions and presents a review of energy-consumption indicators published in the literature. Within the context of Industry 4.0, [8] states that the “environmental backpack” due to the introduction of CPS-related components—that is, computers/servers, peripheral devices, network equipment, additional sensors, batteries, and devices for user interaction—must be put into terms of CO₂-emissions equivalents.

2.4. Energy Efficiency and Consumption. The detailed estimation of energy consumption in a production system is an increasingly important topic for companies aspiring to control their manufacturing power costs [62]. According to [63], energy consumption depends on the resources' activation/deactivation states (influenced by the kind of manufactured product) and their duration and rate (influenced by the process used). Even though there is not a standard approach to monitor the energy consumption in a production system, modelling and simulation are some important methods to perform the what-if scenarios that an energy-efficiency analysis requires [55, 64]. In this case, the continuous paradigm seems to be more suitable for representing the power consumption of single machines [65], while the discrete event simulation is more advantageous for

the analysis of a production system flow [66, 67]. Within the continuous simulation approach, the study in [68] proposed a simulation method to estimate the energy consumption of a virtual machine tool, the study in [44] put this energy consumption in terms of the machining parameters, and [69] used a regression algorithm to relate both of them; the authors in [70] built a simulation model that evaluated the direct/indirect consumed energy when building a product; the authors in [71] presented a simulation model that combines both the continuous and discrete natures of energy consumption present in discrete manufacturing systems; the authors in [72] incorporated real-time production into their simulation model, as many of the previous works performed only offline evaluation, prediction, and optimization of the energy-efficient manufacturing; the authors in [54] presented an online, digital twin-based bidirectional operation framework, proposed to operationalize a truly energy-efficient manufacturing system; the study in [73] proposes an energy-oriented maintenance methodology proposed to reduce energy for the whole line. Regarding the use of discrete event simulation and energy consumption, the authors in [74–77] analyze the energy consumption of a production facility via a production system flow simulation model; the study in [78] proposes the use of process chains for the simulation of energy-oriented manufacturing systems; the study in [79] presents the Energy Blocks simulation methodology, aimed at creating a power (or energy load) profile of each machine's operation state, for creation. It must be noted that these profiles can be developed for single machines [80, 81], or for several machines, in the form of a cumulative load profile [79, 82].

2.5. Sustainable Mass Customization 4.0. The central notion of Industry 4.0 is a rapidly responsive service-oriented manufacturing model, to deal with the dynamic arrival of manufacturing orders for highly customized product, aimed at meeting the customer requirements in a quick and profitable way and considering the environmental and social impacts that guarantee durable competitiveness [13]. In particular, the use of CPS appears to be the answer to the increasing demand for individualized goods produced in small-lot sizes, as the latter requires the use of more flexible resources [7]. Because of the latter, a goal of Industry 4.0—among several others—is the sustainable success in a mass customization market [83], where customers increase variant diversity [84], designed to their individual specifications [85, 86] and without paying a high price premium [87]. Now, the smart components of Industry 4.0 can help reduce the complexity inherent to managing the mass-customization production system [88], via the use of information technologies [89], as long as there is no lack of information quality and availability for the use of these associated technologies [90]. An example of the latter is presented in [91], which presents a systematic framework that integrates a sensor-driven prognostic method and an opportunistic maintenance policy, for a mass customization environment, based on real-time data acquisition and processing.

2.6. Research Features. The previous sections can be summarized as follows: the success of an Industry 4.0 mass customization environment, defined in this paper as a mass customization production system operating within a reconfigurable CPS context, depends on its sustainability (from here we will use the term Sustainable Mass Customization 4.0), where the latter can only be achieved by the manufacturing efficiency of the smart factory-based Industry 4.0 transforming processes [85, 92–94]. Table 1 summarizes the contributions of the authors presented in the previous literature review. From the latter, we can derive the following conclusions:

- (1) Sustainability is understood as a potential benefit of the implementation of the Industry 4.0 paradigm, specifically from the use of high energy-efficiency systems [95]
- (2) Sustainability is considered to be a core element of the business model of Industry 4.0, specifically when its benefits also have an economic benefit
- (3) Eco-efficient manufacturing processes—core element of sustainability—refer to producing “more with less,” using energy-efficient, value creation process chains
- (4) An energy-efficiency analysis requires performing energy-consumption what-if analyses (where simulation is an appropriate approach)

Based on these findings, we identify the following research opportunity: to establish Sustainable Mass Customization 4.0 in the context of an energy-efficient, value creation manufacturing process chain, upon which energy-consumption comparisons can be made. Now, an energy-efficiency analysis is heavily dependent on the production planning and scheduling activity of the production line and factory supporting the value creation manufacturing process chain [55]. This last fact presents a problem: within an Industry 4.0 context, where machines “negotiate” each next production step, the value creation manufacturing process chain can no longer be predefined, as it has to be created ad hoc for each set of manufactured “customer-specific, make-to-order” products [7], making it hard to establish a priori (a generalized) energy-consumption profile for each product to be manufactured.

The core element of an energy-efficient manufacturing requires to perform energy-consumption what-if analyses, and the latter depends on the operative states of the value creation manufacturing process chain, we consider that it becomes necessary to find an alternative way of performing such what-if analyses. For this reason, we propose the use of the entropy-based formulation $\epsilon_{MC4.0}$ [96] as an alternative way of performing the initial steps of the energy-consumption what-if analyses required by an energy-efficient manufacturing process, as its main feature is its ability to act as a fairly good trend indicator of the increase/decrease of the queue length and waiting time in a Mass Customization 4.0 environment. The original contribution of the research work proposed in this paper is the following approach: as within the Energy Blocks methodology, the energy-consumption calculation is based on the required power P —based on a

TABLE 1: Literature review summarizing table.

Topic addressed: sustainability and . . .	References
Smart factory	[7, 9–13]
Industry 4.0	[16–20]
CPS	[15, 21–25]
IoT and Big Data analytics	[26–32]
DES and sustainability	[33–38]
Value creation	[39–44]
DES and value creation	[45–53]
Energy-efficient manufacturing	[54–57]
Energy consumption efficiency	[62–73]
DES and energy consumption	[74–82]
Mass Customization and Industry 4.0	[83–91]

TABLE 2: Manufacturing process routes.

Product number	Manufacturing process routes
1	$3M_2 + 3M_4$
2	$4M_3 + 4M_4$
3	$2M_1 + 2M_2 + 2M_4$
4	$2M_1 + 4M_3 + 6M_4$
5	$2M_1 + 1M_2 + 2M_3 + 5M_4$
6	$1M_1 + 2M_2 + 2M_3 + 7M_4$
7	$3M_1 + 3M_2 + 6M_4$
8	$3M_1 + 6M_3 + 9M_4$
9	$3M_1 + 1M_2 + 4M_3 + 8M_4$
10	$2M_1 + 3M_2 + 2M_3 + 9M_4$

measured average value or taken from a vendor specification [79]—and the duration T of the operation state; the use of $\epsilon_{MC4.0}$ expression allows the comparisons of energy-consumption trends for different production scenarios. The usefulness of the proposed approach is demonstrated by comparing the results of a discrete-event simulation model of Mass Customization 4.0 environment (regarding the operating states of the system) and the values obtained by using the $\epsilon_{MC4.0}$ expression. The rest of the paper is organized as follows: Section 2 presents the case of a Mass Customization 4.0 environment and the discrete-event simulation (DES) model built with the idea of generating statistical output that reflects the behavior of the system. Sections 3 introduces the $\epsilon_{MC4.0}$ expression and tests its validity. Deriving from the obtained results, Section 4 presents the final conclusions and the identified future research venues.

3. Mass Customization 4.0 Environment

The details of the Mass Customization 4.0 environment to be analyzed, as well as the discrete-event simulation (DES) model built to collect statistical data about the system’s performance—measured in terms of the manufacturing resources’ queue length and the products’ waiting time—can be found in [96] (a brief summary is presented in Appendix A). In this case, Table 2 shows the manufacturing process routes for each of the manufactured products, in terms of type of manufacturing resource M_i used (Figure 1) and processing time (i.e., product 1B uses manufacturing resource M_2 for three time units, followed by the use of manufacturing resource M_4 for three time units).

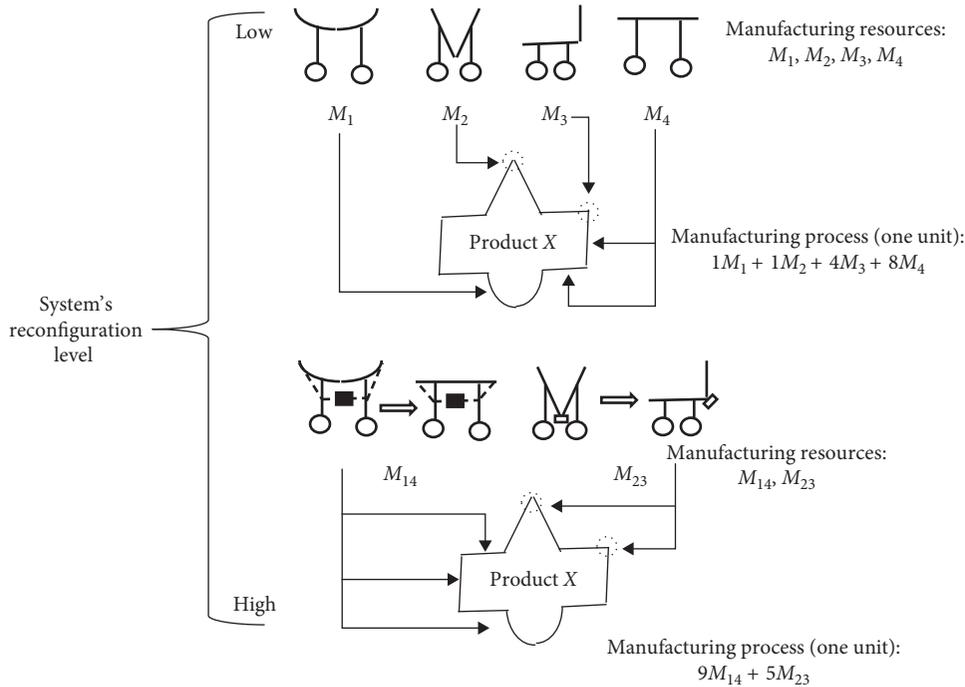


FIGURE 1: Types of manufacturing resources used by the Mass Customization 4.0 environment, adapted from [96].

In order to reflect the “smart” side of the Mass Customization 4.0 environment, the discrete-event simulation model allows manufacturing resources to “talk” to each other, and they decide which product is processed next by each one of them. Figure 2 refers to the machine-to-machine operation mode, and each manufacturing resource drags to its waiting queue the type of product that is more convenient to be processed next. For example, M_{23} drags Product 2A1B1C from M_2 waiting queue (for the same reason expressed above) and M_2 proceeds in a similar way (dragging Product 1B from M_{23} waiting queue). See Appendix A for the details of how this was implemented in the DES.

The following operational conditions were used:

- (i) The Mass Customization 4.0 environment is assumed to be operating continuously; that is, breakdowns, changeover, setup, and load/unload times are assumed to be negligible, and each manufacturing resource is capable of processing only one unit at a time
- (ii) All the manufacturing resources were subject to certain degree of variation (reflected as an exponential normal distribution for the processing times)
- (iii) A simulation run time, long enough to allow the total processing of twelve units of each product type, was used
- (iv) Thirty replications were used in order to avoid significant variation in the observed results

The simulation run output was examined for reasonableness, according to the verification and validation approach suggested by [97]. Confidence intervals of 90% were

used in order to provide the proper statistical basis for making inferences and conclusions. Two different scenarios were tested under these operative conditions (Table 3): Scenario #1, sequential (in terms of increasing level of complexity), and Scenario #2, totally random.

3.1. Entropy-Based Formulation $\epsilon_{MC4.0}$. As mentioned in Section 2.5, we propose the use of the entropy-based formulation $\epsilon_{MC4.0}$ [96] as an alternative way of performing the initial steps of the energy-consumption what-if analyses required by an energy-efficient manufacturing process, as its main feature is its ability to act as a fairly good trend indicator of the increase/decrease of the queue length and waiting time in a Mass Customization 4.0 environment. This $\epsilon_{MC4.0}$ expression takes the following form:

$$\epsilon_{MC4.0} = \left(\frac{1}{P_i}\right) * \log_2\left(\frac{1}{P_i}\right), \quad (1)$$

where P_i depends upon the processing time of each product’s manufacturing process route. As there can be multiple alternative manufacturing process routes for the same product, Table 4 presents the frequency of occurrence of each alternative route (Scenario #1) and the corresponding processing time for each case. The frequency of occurrence was obtained by running enough number of simulations’ replications until no significant variation of these values was observed. In this way, regarding Table 4, product P_3 has a corresponding manufacturing process route of $2M_1 + 2M_2 + 2M_4$, where

- (i) the two minutes for M_1 , 49.4% of the times, come from M_1 (0.459 + 0.02 + 0.492 + 0.009) and, 50.6% of the times, come from M_{14} (1.02)

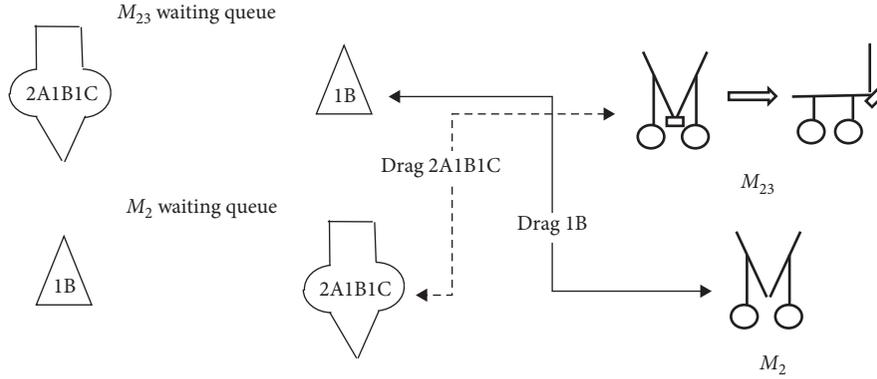


FIGURE 2: Machine-to-machine operation mode, adapted from [96].

TABLE 3: Tested scenarios.

Scenario #1	Products involved	Scenario #2	Number of units produced
1		6	12
1, 2		6, 2	24
1, 2, 3		6, 2, 3	36
1, 2, 3, 7		6, 2, 3, 10	48
1, 2, 3, 7, 4		6, 2, 3, 10, 4	60
1, 2, 3, 7, 4, 8		6, 2, 3, 10, 4, 1	72
1, 2, 3, 7, 4, 8, 5		6, 2, 3, 10, 4, 1, 7	84
1, 2, 3, 7, 4, 8, 5, 6		6, 2, 3, 10, 4, 1, 7, 9	96
1, 2, 3, 7, 4, 8, 5, 6, 9		6, 2, 3, 10, 4, 1, 7, 9, 5	108
1, 2, 3, 7, 4, 8, 5, 6, 9, 10		6, 2, 3, 10, 4, 1, 7, 9, 5, 8	120

(ii) The two minutes for M_2 , 49.8% of the times, come from M_2 ($0.459 + 0.020 + 0.519$) and, 50.2% of the times, come from M_{23} ($0.492 + 0.018 + 0.492$)

(iii) The two minutes for M_4 , 47.5% of the times, come from M_4 ($0.459 + 0.492$) and, 52.5% of the times, come from M_{14} ($0.020 + 0.018 + 1.002$)

Table 5 shows the calculation of P_i for the case of manufacturing resource M_1 . It must be noted that whenever a product processing time appears as NA, we consider its contribution to the $\varepsilon_{MC4.0}$ expression value to be negligible. Plugging these probabilities P_i into the $\varepsilon_{MC4.0}$ expression, we obtain the values shown in Table 6. Appendix B, at the end of this document, shows the steps for the calculation of the values presented in Tables 4–6 in more detail.

4. Scenario Results and Analysis

In order to assess the level of usefulness of the $\varepsilon_{MC4.0}$ expression to the what-if analyses required by an energy-efficient manufacturing process, that is, the comparisons of energy consumption trends for different production scenarios, two scenarios were tested: Scenario #1, where the increasing level of complexity is sequential, and Scenario #2, where the increasing level of complexity is totally random. For Scenario #1, Table 7 shows the simulation results of the six manufacturing resources M_i and Table 8 shows their respective $\varepsilon_{MC4.0}$ values. Appendix C, at the end of this document, shows the steps for the calculation of the values

presented in Table 8 in more detail. It must be noted that this sequence of steps—as well as the incoming/outgoing conditions mentioned in this section—is an original contribution of this research effort, as they are not part of the original way of calculating the $\varepsilon_{MC4.0}$ values, as presented in [96]. Figures 3(a) through 3(f) show the normalized values presented in these tables, where W_t is waiting time and L_q is queue length. In a similar way, Figures 4(a) through 4(f) show the case for Scenario #2.

4.1. Analysis of Scenarios #1 and #2. For both Scenarios #1 and #2, the following facts can be observed:

- (i) The normalized values of the $\varepsilon_{MC4.0}$ expression follow closely the trend of the normalized values of W_t and L_q for manufacturing resources M_1 , M_4 , and M_{14} . Also, these values follow an always-increasing trend. A look at the products processed by these manufacturing resources reveals that these products have no associated W_t and L_q decrease points (see Appendix C for a further explanation of these decrease points).
- (ii) The normalized values of the $\varepsilon_{MC4.0}$ expression do not follow closely the trend of the normalized values of W_t and L_q for manufacturing resources M_2 , M_3 , and M_{23} . Also, these values follow an alternating increasing/decreasing trend. A look at the products processed by these manufacturing resources reveals

TABLE 4: Frequency of occurrence of alternative manufacturing process routes and related processing times: Scenario #1.

	P_k			P_k			P_k			P_k			P_k			P_k			P_{10}															
%	0.445	0.038	0.478	0.071	0.040	0.002	0.229	0.010	0.246	0.009	0.259	0.246	0.424	0.018	0.493	0.025	0.021	0.019	0.417	0.016	0.063	0.001	0.269	0.234	0.409	0.007	0.088	0.0	0.228	0.268				
M_1	1.335	0.115					0.459	0.020	0.492	0.009	0.519		1.273	0.054	1.478	0.075	0.063		0.834	0.032	0.126	0.003	1.227	0.021	0.263									
M_2	1.335			0.283			0.459						1.273						1.668				1.077		2.455	0.043	1.368							
M_3							0.459	0.020	0.492	0.018	1.038	0.984	2.546	0.109	2.957	0.151	0.189	0.167	2.501	0.097	0.377	0.008	2.153	1.869	3.682	0.064	0.788	2.736	3.218					
M_4	1.435	0.114		0.283			0.459	0.020	0.492	0.018	1.038	0.984	2.546	0.109	2.957	0.151	0.189	0.167	2.501	0.097	0.377	0.008	2.153	1.869	3.682	0.064	0.788	2.736	3.218					
M_{14}	1.435	0.114		0.283			0.459	0.020	0.492	0.018	1.038	0.984	2.546	0.109	2.957	0.151	0.189	0.167	2.501	0.097	0.377	0.008	2.153	1.869	3.682	0.064	0.788	2.736	3.218					
M_{15}	1.435	0.114		0.283			0.459	0.020	0.492	0.018	1.038	0.984	2.546	0.109	2.957	0.151	0.189	0.167	2.501	0.097	0.377	0.008	2.153	1.869	3.682	0.064	0.788	2.736	3.218					
M_1	1.45			M_2			0.989	M_2	0.998				2.881	M_2	1.391				0.994	M_2		0.251	0.934		1.512	M_2	0.525	1.609						
M_2	2.77			M_4	3.71		0.989	M_2	0.998				2.881	M_2	1.391				0.994	M_2		0.251	0.934		1.512	M_2	0.525	1.609						
M_4	2.77			M_4	3.71		0.989	M_2	0.998				2.881	M_2	1.391				0.994	M_2		0.251	0.934		1.512	M_2	0.525	1.609						
M_{14}	1.55			M_{15}	1.666		2.060	M_{15}	1.002				0.616	M_{15}	1.609				4.127	M_{15}	1.191	6.018	M_{15}	2.134										
%	0.198	0.001	0.023	0	0.142	0.104	0.272	0.215	0	0.022	0	0.265	0	0.147	0.108	0.244	0.223	0	0.020	0.0	0.258	0	0.137	0.121	0.242	0.193	0	0.019	0	0.262	0	0.14	0.113	0.273
M_1	0.396	0.001	0.047	0.521						0.022		0.265				0.668			0.061		0.773				0.386			0.039			0.523			
M_2	0.198	0.001	0.023	0.142	0.104		0.272	0.215		0.022		0.265	0.293	0.216		0.223			0.020		0.773				0.386			0.039			0.523			
M_3	0.396	0.001	0.023	0.283						0.043		0.265	0.293	0.216		0.223			0.020		0.773				0.386			0.039			0.523			
M_4	0.989	0.001	0.117	0.283			1.505	1.505		0.151		1.857	0.293	0.216		0.890			0.163		2.062				0.386			0.039			0.523			
M_{14}	0.003			0.992	0.725	1.904				0.151		1.857	1.173	0.863	1.950	1.780			0.163		2.062				0.386			0.039			0.523			
M_{15}	0.047			0.207	0.816		0.816			0.043		1.061	1.173	0.863	1.950	1.780			0.163		2.062				0.386			0.039			0.523			
M_1	0.965	M_2	0.467	0.680	M_4	2.410				0.982		1.061	1.173	0.863	1.950	1.780			0.163		2.062				0.386			0.039			0.523			
M_2	0.680	M_4	2.410	0.680	M_4	2.410				0.982		1.061	1.173	0.863	1.950	1.780			0.163		2.062				0.386			0.039			0.523			
M_4	3.625	M_{23}	1.852	3.986	M_{23}	2.295				2.295		1.061	1.173	0.863	1.950	1.780			0.163		2.062				0.386			0.039			0.523			
				3.986	M_{23}	2.295				2.295		1.061	1.173	0.863	1.950	1.780			0.163		2.062				0.386			0.039			0.523			
				3.986	M_{23}	2.295				2.295		1.061	1.173	0.863	1.950	1.780			0.163		2.062				0.386			0.039			0.523			
				3.986	M_{23}	2.295				2.295		1.061	1.173	0.863	1.950	1.780			0.163		2.062				0.386			0.039			0.523			
				3.986	M_{23}	2.295				2.295		1.061	1.173	0.863	1.950	1.780			0.163		2.062				0.386			0.039			0.523			
				3.986	M_{23}	2.295				2.295		1.061	1.173	0.863	1.950	1.780			0.163		2.062				0.386			0.039			0.523			
				3.986	M_{23}	2.295				2.295		1.061	1.173	0.863	1.950	1.780			0.163		2.062				0.386			0.039			0.523			
				3.986	M_{23}	2.295				2.295		1.061	1.173	0.863	1.950	1.780			0.163		2.062				0.386			0.039			0.523			
				3.986	M_{23}	2.295				2.295		1.061	1.173	0.863	1.950	1.780			0.163		2.062				0.386			0.039			0.523			
				3.986	M_{23}	2.295				2.295		1.061	1.173	0.863	1.950	1.780			0.163		2.062				0.386			0.039			0.523			
				3.986	M_{23}	2.295				2.295		1.061	1.173	0.863	1.950	1.780			0.163		2.062				0.386			0.039			0.523			
				3.986	M_{23}	2.295				2.295		1.061	1.173	0.863	1.950	1.780			0.163		2.062				0.386			0.039			0.523			
				3.986	M_{23}	2.295				2.295		1.061	1.173	0.863	1.950	1.780			0.163		2.062				0.386			0.039			0.523			
				3.986	M_{23}	2.295				2.295		1.061	1.173	0.863	1.950	1.780			0.163		2.062				0.386			0.039			0.523			
				3.986	M_{23}	2.295				2.295		1.061	1.173	0.863	1.950	1.780			0.163		2.062				0.386			0.039			0.523			
				3.986	M_{23}	2.295				2.295		1.061	1.173	0.863	1.950	1.780			0.163		2.062				0.386			0.039			0.523			
				3.986	M_{23}	2.295				2.295		1.061	1.173	0.863	1.950	1.780			0.163		2.062				0.386			0.039			0.523			
				3.986	M_{23}	2.295				2.295		1.061	1.173	0.863	1.950	1.780			0.163		2.062				0.386			0.039			0.523			
				3.986	M_{23}	2.295				2.295		1.061	1.173	0.863	1.950	1.780			0.163		2.062				0.386			0.039			0.523			
				3.986	M_{23}	2.295				2.295		1.061	1.173	0.863	1.950	1.780			0.163		2.062				0.386			0.039			0.523			
				3.986	M_{23}	2.295				2.295		1.061	1.173	0.863	1.950	1.780			0.163		2.062				0.386			0.039			0.523			
				3.986	M_{23}	2.295				2.295		1.061	1.173	0.863	1.950	1.780			0.163		2.062				0.386			0.039			0.523			
				3.986	M_{23}	2.295				2.295		1.061	1.173	0.863	1.950	1.780			0.163		2.062				0.386			0.039			0.523			
				3.986	M_{23}	2.295				2.295		1.061	1.173	0.863	1.950	1.780			0.163		2.062				0.386			0.039			0.523			
				3.986	M_{23}	2.295				2.295		1.061	1.173	0.863	1.950	1.780			0.163		2.062				0.386			0.039			0.523			
				3.986	M_{23}	2.295				2.295		1.061	1.173	0.863	1.950	1.780			0.163		2.062				0.386			0.039			0.523			
				3.986	M_{23}	2.295				2.295		1.061	1.173	0.863	1.950	1.780			0.163		2.062				0.386			0.039			0.523			
				3.986	M_{23}	2.295				2.295		1.061	1.173	0.863	1.950	1.780			0.163		2.062				0.3									

TABLE 5: Probabilities P_i for Scenario #1.

Product number	1	2	3	7	4	8	5	6	9	10
Processing time on M_1 (from Table 4)	0	0	0.989	2.8810	0.994	1.5120	0.965	0.502	1.502	0.948
Σ processing time	0	0	0.989	3.87	4.864	6.376	7.341	7.843	9.345	10.293
P_1	0	0	0	0	0	0	0	0	0	0
P_2		0	0	0	0	0	0	0	0	0
P_3			1.0	0.2556	0.2033	0.1551	0.1347	0.1261	0.1058	0.0961
P_7				0.7444	0.5923	0.4519	0.3925	0.3673	0.3083	0.2799
P_4					0.2044	0.1559	0.1354	0.1267	0.1064	0.0966
P_8						0.2371	0.206	0.1928	0.1618	0.1469
P_5							0.1315	0.123	0.1033	0.0938
P_6								0.064	0.0537	0.0488
P_9									0.1607	0.1459
P_{10}										0.0921

TABLE 6: $\epsilon_{MC4.0}$ values for manufacturing resource M_1 : Scenario #1.

Product number	1	2	3	7	4	8	5	6	9	10
P_1	0	0	0	0	0	0	0	0	0	0
P_2		0	0	0	0	0	0	0	0	0
P_3			0	7.702	11.3023	17.3332	21.4658	23.6905	30.616	35.1726
P_7				0.5719	1.2756	2.5364	3.4384	3.9333	5.5065	6.5632
P_4					11.2098	17.1994	21.3041	23.5139	30.3936	34.9203
P_8						8.7576	11.0645	12.3175	16.2405	18.8366
P_5							22.2693	24.5677	31.7206	36.4254
P_6								61.9573	78.5284	89.3529
P_9									16.4086	19.0284
P_{10}										37.357
Calculated $\epsilon_{MC4.0}$ for M_1	0	0	0	8.2739	23.7878	45.8266	79.5421	149.9802	209.4142	277.6564

TABLE 7: Simulation results for all the manufacturing resources M_i .

Manufacturing resource type	Performance measure	Product number									
		1	2	3	7	4	8	5	6	9	10
M_1	W_t	0	0	6.5555	16.7374	22.3501	34.211	38.1327	40.777	52.5974	55.7325
	L_q	0	0	0.0449	0.2878	0.536	1.001	1.3217	1.6678	2.4893	2.9629
M_2	W_t	7.2041	6.4513	9.4515	13.3579	8.3426	5.6211	7.4244	5.4951	3.7811	3.846
	L_q	0.0432	0.0368	0.116	0.2889	0.167	0.1078	0.2005	0.1731	0.1448	0.1737
M_3	W_t	0	18.9792	17.938	19.0161	26.8543	31.5524	25.827	30.7712	30.7287	27.4828
	L_q	0	0.2324	0.2035	0.2091	0.5644	0.9102	0.7781	1.0191	1.2696	1.2567
M_4	W_t	5.6414	14.6375	24.9271	37.8379	56.0045	62.462	73.3359	91.6748	96.5603	108.82
	L_q	0.0431	0.2379	0.6643	1.3539	2.5763	3.3135	4.3029	6.0045	6.8901	8.4422
M_{14}	W_t	0	0	13.4523	16.2064	32.2558	59.3078	82.6413	109.73	131.34	169.05
	L_q	0	0	0.0954	0.2038	0.5943	1.4249	2.5032	3.9559	5.5615	8.1669
M_{23}	W_t	8.1309	10.1165	10.6185	7.2890	6.2652	7.1726	7.3475	7.1277	7.2941	9.3542
	L_q	0.0488	0.0637	0.1390	0.1448	0.1180	0.1331	0.1920	0.2202	0.2731	0.4132

that these products have a lot of associated W_t and L_q decrease points (see Appendix C for a further explanation of these decrease points).

Moreover, Table 9 presents a segmentation of the normalized values of both queue length Q_i and waiting time W_t and the frequency upon which both Scenarios #1 and #2 fall into those value ranges. In this way, for example, for manufacturing resource M_2 , with queue length Q_i , Scenario #1 values fall 50% of the times in the 0.4–0.6 segment, while, for Scenario #2, the values fall 40% of the times in the 0.0–0.2 segment, leaving the impression that Scenario #2 presents advantages compared to Scenario #1. However, for this same case, Scenario #1 values fall only 10% of the times in the

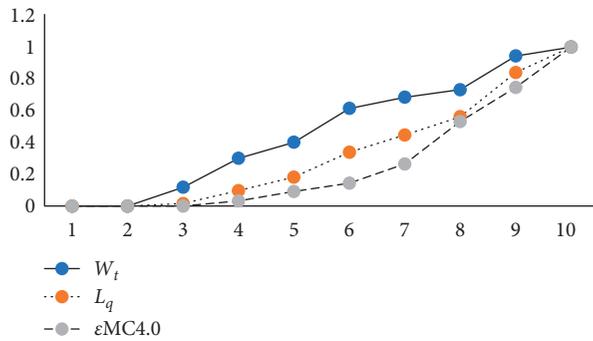
0.8–1.0 segment, while, for Scenario #2, the values fall 30% of the times in the same segment. A similar analysis can be made for the rest of the manufacturing resources present in Table 9.

4.2. Managerial Implications. The previous section can be summarized as follows:

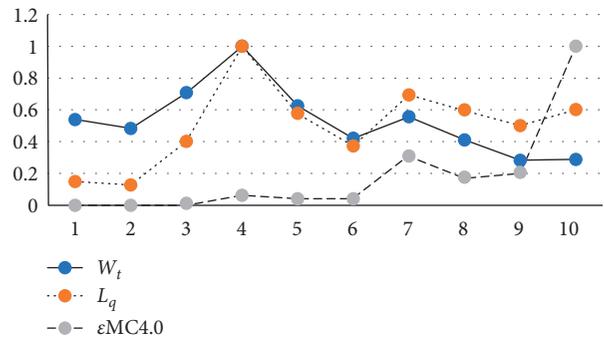
- (1) The $\epsilon_{MC4.0}$ expression acts as a fairly good trend indicator of the system’s performance parameters increase/decrease but not as an estimator of the final values, something that is consistent with previous reported findings in [98, 99]

TABLE 8: $\epsilon_{MC4.0}$ values for all the manufacturing resources M_i .

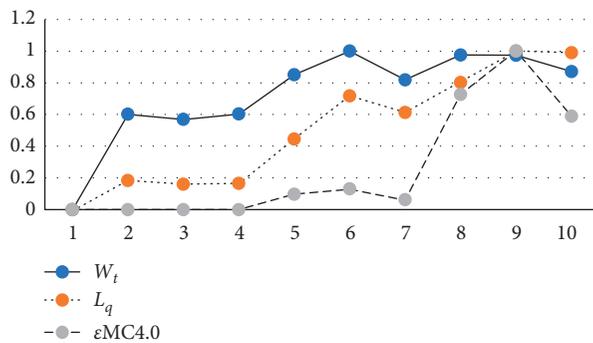
Manufacturing resource type	$\epsilon_{MC4.0}$ value	Product number									
		1	2	3	4	5	6	7	8	9	10
M_1	Actual	0	0	0	8.2739	23.7878	37.069	68.4776	137.6627	193.1738	258.8198
	Normalized	0	0	0	0.0319	0.0919	0.1432	0.2645	0.5318	0.7463	1
M_2	Actual	0	0	4.4735	23.5629	15.289	15.289	116.8177	66.5368	78.0648	378.0477
	Normalized	0	0	0.012	0.0623	0.0404	0.0404	0.309	0.176	0.2064	1
M_3	Actual	0	0	0	0	19.5996	26.3977	12.4518	147.0566	202.5393	119.2279
	Normalized	0	0	0	0	0.0968	0.1303	0.0614	0.72606	1	0.5886
M_4	Actual	0	4.2736	29.0028	70.7731	112.8776	176.3542	236.7679	376.6965	507.336	618.8529
	Normalized	0	0.0069	0.0469	0.1143	0.1824	0.2849	0.3825	0.6087	0.8198	1
M_{14}	Actual	0	2.6608	43.596	68.0447	163.2748	350.9033	506.0436	683.4897	911.5257	1118.5575
	Normalized	0	0.0023	0.0389	0.0608	0.14596	0.3137	0.4524	0.61104	0.8149	1
M_{23}	Actual	0	0.1625	5.8944	19.4237	10.8321	22.4809	64.382	112.811	155.7389	159.6592
	Normalized	0	0.00101	0.0369	0.1216	0.0678	0.1408	0.4032	0.7065	0.9754	1



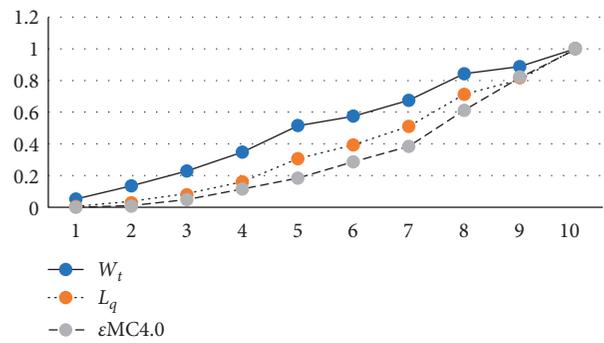
(a)



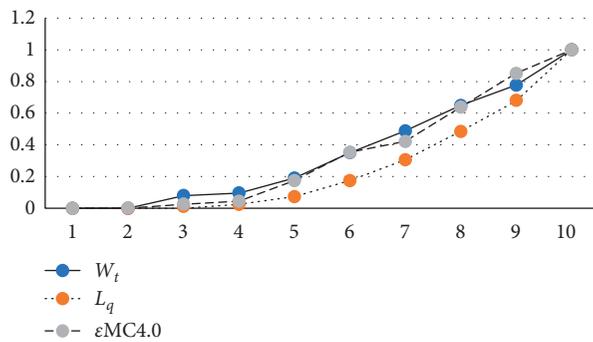
(b)



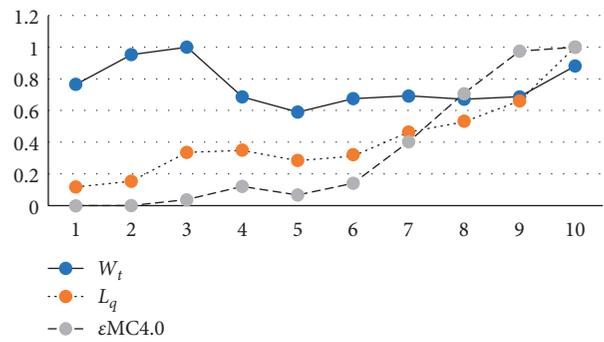
(c)



(d)



(e)



(f)

FIGURE 3: (a). M_1 $\epsilon_{MC4.0}$ values behavior. (b) M_2 $\epsilon_{MC4.0}$ values behavior. (c) M_3 $\epsilon_{MC4.0}$ values behavior. (d) M_4 $\epsilon_{MC4.0}$ values behavior. (e) M_{14} $\epsilon_{MC4.0}$ values behavior. (f) M_{23} $\epsilon_{MC4.0}$ values behavior.

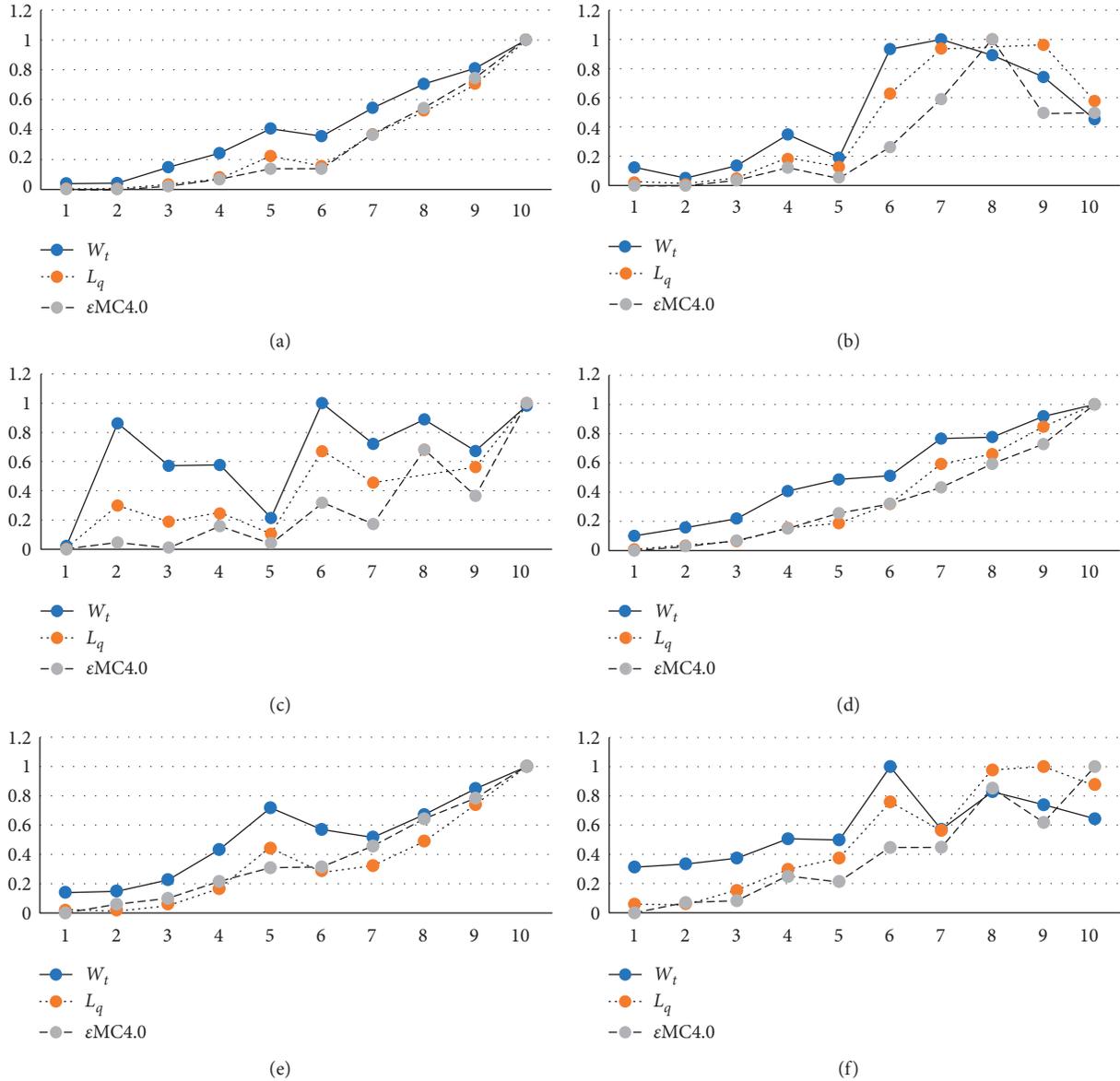


FIGURE 4: (a) $M_1 \varepsilon_{MC4.0}$ values behavior. (b) $M_2 \varepsilon_{MC4.0}$ values behavior. (c) $M_3 \varepsilon_{MC4.0}$ values behavior. (d) $M_4 \varepsilon_{MC4.0}$ values behavior. (e) $M_{14} \varepsilon_{MC4.0}$ values behavior. (f) $M_{23} \varepsilon_{MC4.0}$ values behavior.

- (2) The accuracy of the trend indicator depends on the mix of products processed by these manufacturing resources and the number of W_t and L_q decrease points associated with these products
- (3) Depending on the managerial objectives of the Mass Customization 4.0 environment, there could be a sequence of products—to be processed by the manufacturing resources—that present advantages, in terms of minimizing the queue length Q_l and waiting time W_t normalized values or, on the other hand, that stabilize these values around a desired level of performance

If, as mentioned by [100], developing a production program/schedule is about to squeeze products through

available resources—which often result in unfeasible or difficult-to-follow schedules [101]—it is our belief that the $\varepsilon_{MC4.0}$ expression is promising in the area of flexible job shop scheduling, where the machine assignment and operation sequencing represent a very complex problem (in fact, traditional mathematic optimization methods are difficult to tackle within a reasonable amount of time [102], due to the flexibility exhibited by the manufacturing system (something of a proper Mass Customization 4.0 environment)). By using the $\varepsilon_{MC4.0}$ expression as a basis, a methodology to perform the what-if analyses is required by an energy-efficient manufacturing system, in terms of the time spent in specific operative states, as they are strongly related to energy consumption.

TABLE 9: Segmentation frequency of Q_t and W_t normalized values for Scenarios #1 and #2.

	M_2-Q_t		M_3-Q_t		$M_{23}-Q_t$		M_2-W_t		M_3-W_t		$M_{23}-W_t$	
	Sequential	Random	Sequential	Random	Sequential	Random	Sequential	Random	Sequential	Random	Sequential	Random
0.0-0.2	0	4	1	1	0	0	2	2	4	3	2	3
0.2-0.4	2	1	0	1	0	4	1	0	0	2	4	2
0.4-0.6	5	1	1	2	1	3	4	1	1	2	2	1
0.6-0.8	2	1	2	2	6	1	2	1	2	2	1	1
0.8-1.0	1	3	6	4	3	2	1	3	3	1	1	3

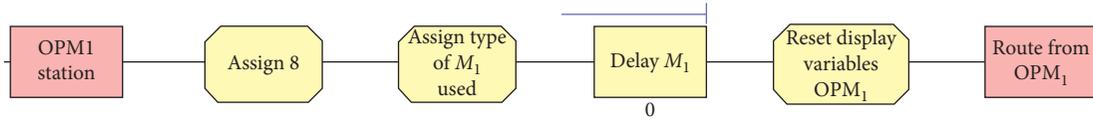


FIGURE 5: Excerpt of the DES model: manufacturing resource M_1 case.

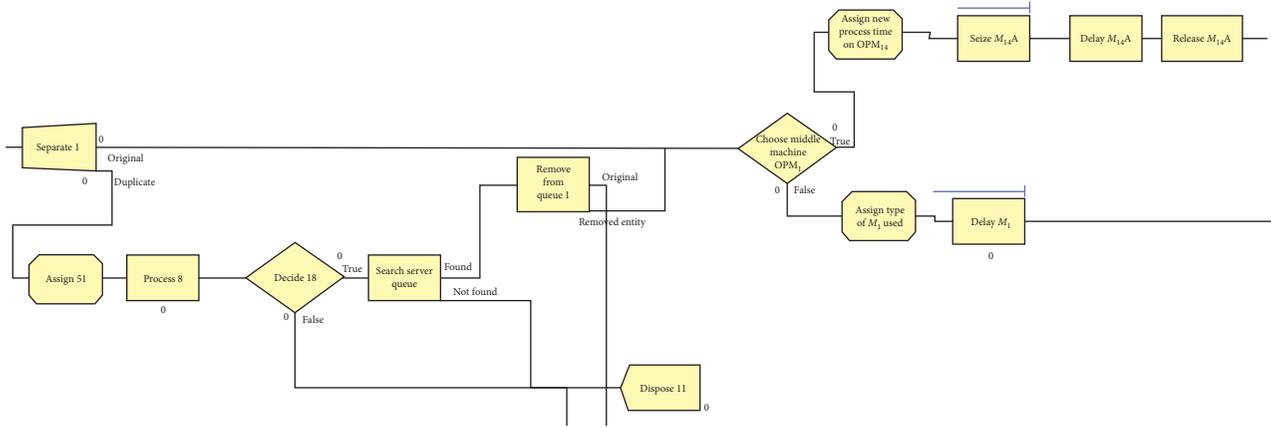


FIGURE 6: Excerpt of the DES model: manufacturing resources M_1 and M_{14} case.

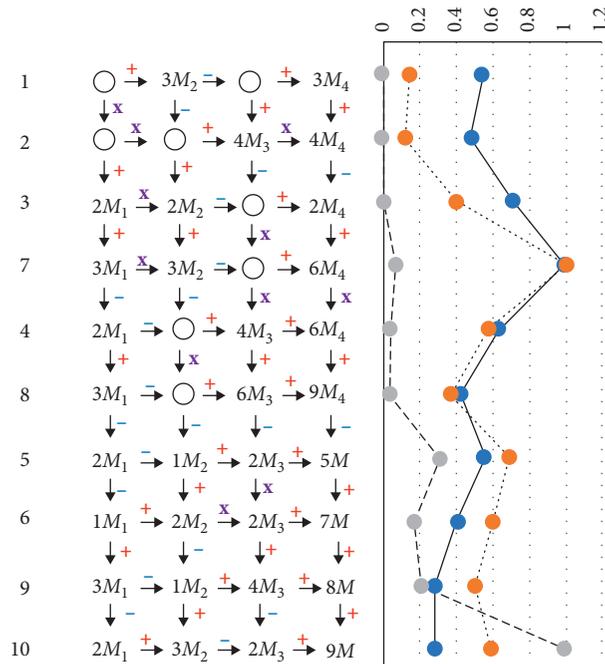


FIGURE 7: Behavior of manufacturing resource M_2 (W_t , L_q , and $\epsilon_{MC}4.0$ normalized values).

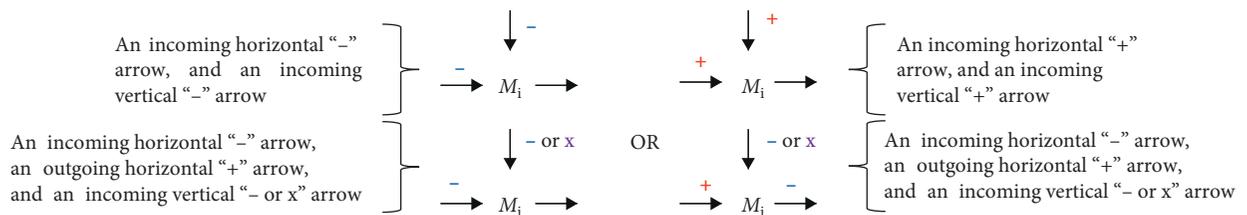


FIGURE 8: Incoming/outgoing conditions of Case #1.

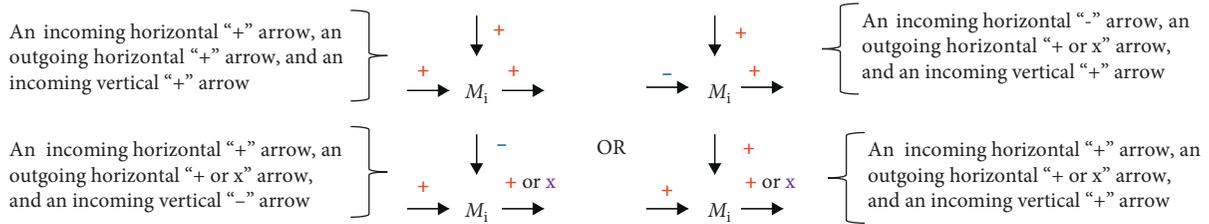


FIGURE 9: Incoming/outgoing conditions of Case #2.

TABLE 10: Probabilities P_i for M_2 : Scenario #1.

Product number	1	2	3	7	4	8	5	6	9	10
Processing time on M_2 (from Table 4)	1.45	0	0.989	1.391	0	0	0.467	0.982	0.59	1.397
Σ processing time	1.45	1.45	2.439	3.83	3.83	3.83	4.297	5.279	5.869	7.266
P_1	1	1	0.5945	0.3786	0.3786	0.3786	0.3374	0.2747	0.2471	0.1996
P_2		0	0	0	0	0	0	0	0	0
P_3			0.4055	0.2582	0.2582	0.2582	0.2302	0.1873	0.1685	0.1361
P_7				0.3632	0.3632	0.3632	0.3237	0.2635	0.237	0.1914
P_4					0	0	0	0	0	0
P_8						0	0	0	0	0
P_5							0.1087	0.0885	0.0796	0.0643
P_6								0.186	0.1673	0.1352
P_9									0.1005	0.0812
P_{10}										0.1923
Calculated $\epsilon_{MC4.0}$ for M_2	0	0	4.4735	15.2890	15.2890	15.2890	48.3401	66.5368	78.0648	119.2279

TABLE 11: Final $\epsilon_{MC4.0}$ values for M_2 : Scenario #1.

Product number	1	2	3	7	4	8	5	6	9	10
Calculated $\epsilon_{MC4.0}$ for M_1	0	0	0	8.2739	23.7878	45.8266	79.5421	149.9802	209.4142	277.6564
Calculated $\epsilon_{MC4.0}$ for M_2	0	0	4.4735	15.289	15.289	15.289	48.3401	66.5368	78.0648	119.2279
Criteria for final $\epsilon_{MC4.0}$ for M_2	Σ	Smallest		Σ	Smallest	Smallest	Σ	Smallest	Smallest	Σ
Final $\epsilon_{MC4.0}$ for M_2	0	0	4.4735	23.5629	15.289	15.289	116.8177	66.5368	78.0648	378.0477

TABLE 12: Final $\epsilon_{MC4.0}$ values for M_3 : Scenario #1.

Product number	1	2	3	7	4	8	5	6	9	10
Calculated $\epsilon_{MC4.0}$ for M_2	0	0	4.4735	15.289	15.289	15.289	48.3401	66.5368	78.0648	119.2279
Calculated $\epsilon_{MC4.0}$ for M_3	0	0	0	0	4.3106	11.1087	12.4518	80.5198	124.4745	133.351
Criteria for final $\epsilon_{MC4.0}$ for M_3	Σ	Smallest	Smallest		Σ	Smallest		Σ	Smallest	
Final $\epsilon_{MC4.0}$ for M_3	0	0	0	0	19.5996	26.3977	12.4518	147.0556	202.5393	119.2279

TABLE 13: Final $\epsilon_{MC4.0}$ values for M_4 : Scenario #1.

Product number	1	2	3	7	4	8	5	6	9	10
Calculated $\epsilon_{MC4.0}$ for M_3	0	0	0	0	4.3106	11.1087	12.4518	80.5198	124.4745	133.351
Calculated $\epsilon_{MC4.0}$ for M_4	0	4.2736	29.0028	70.7731	108.5670	165.2672	224.3161	296.1767	382.8615	483.5019
Criteria for final $\epsilon_{MC4.0}$ for M_4						Σ				
Final $\epsilon_{MC4.0}$ for M_4	0	4.2736	29.0228	70.7731	112.8776	176.3542	236.7679	376.6965	507.3360	616.8529

TABLE 14: Probabilities P_i for M_{23} : Scenario #1.

Product number	1	2	3	7	4	8	5	6	9	10
Processing time on M_{23} (from Table 4)	1.55	0.166	1.002	1.6090	1.191	2.1340	1.852	2.295	3.061	2.937
Σ processing time	1.55	1.716	2.718	4.327	5.518	7.652	9.504	11.799	14.86	17.797
P_1	1	0.9033	0.5703	0.3582	0.2809	0.2026	0.1631	0.1314	0.1043	0.0871
P_2		0.0967	0.0611	0.0384	0.0301	0.0217	0.0175	0.0141	0.0112	0.0093
P_3			0.3687	0.2316	0.1816	0.1309	0.1054	0.0849	0.0674	0.0563
P_7				0.3719	0.2916	0.2103	0.1693	0.1364	0.1083	0.0904
P_4					0.2158	0.1556	0.1253	0.1009	0.0801	0.0669
P_8						0.2789	0.2245	0.1809	0.1436	0.1199
P_5							0.1949	0.157	0.1246	0.1041
P_6								0.1945	0.1544	0.129
P_9									0.206	0.172
P_{10}										0.165
Calculated $\epsilon_{MC4.0}$ for M_{23}	0	0.1625	1.4209	4.1347	6.5215	11.3722	16.0419	22.2912	31.2644	40.4313

TABLE 15: Final $\epsilon_{MC4.0}$ values for M_{14} : Scenario #1.

Product number	1	2	3	7	4	8	5	6	9	10
Calculated $\epsilon_{MC4.0}$ for M_1	0	0	0	8.2739	23.7878	37.0690	68.477	137.662	193.173	258.819
Calculated $\epsilon_{MC4.0}$ for M_4	0	4.2736	29.0028	70.7731	108.5670	165.2672	224.316	296.176	382.861	483.501
Calculated $\epsilon_{MC4.0}$ for M_{14}	0	4.1714	67.5822	104.2176	327.0243	715.4645	980.969	1291.567	1737.388	2232.893
Criteria for final $\epsilon_{MC4.0}$ for M_{14}						Σ				
Final $\epsilon_{MC4.0}$ for M_{14}	0	8.4950	96.585	112.491	435.591	880.731	1049.446	1587.744	2120.249	2491.713

TABLE 16: Final $\epsilon_{MC4.0}$ values for M_{23} : Scenario #1.

Product number	1	2	3	7	4	8	5	6	9	10
Calculated $\epsilon_{MC4.0}$ for M_2	0	0	4.4735	15.289	15.289	15.289	48.3401	66.5368	78.0648	119.2279
Calculated $\epsilon_{MC4.0}$ for M_3	0	0	0	0	4.3106	11.1087	12.4518	80.5198	124.4745	133.351
Calculated $\epsilon_{MC4.0}$ for M_{23}	0	0.1625	1.4209	4.1347	6.5215	11.3722	16.0489	22.2912	31.2644	40.4313
Criteria for final $\epsilon_{MC4.0}$ for M_{23}						Σ all not in red				
Final $\epsilon_{MC4.0}$ for M_4	0	0.1625	5.8944	19.4237	10.8321	22.4809	64.382	112.811	155.7389	159.6592

5. Conclusions and Future Research

The concept of mass customization imposes a series of pressures due to the fact that customers want to have the opportunity to design their own products/services without a high price premium. Now, even though Industry 4.0 aims to ensure the competitiveness within this environment, its ultimate success depends on its level of sustainability, achieved through the use of an energy-efficient manufacturing process. The latter requires performing energy-consumption what-if analyses, which are hard to perform as the value creation manufacturing process chain cannot longer be predefined (due to the use of highly flexible and reconfigurable CPS). The original contribution of this paper is the use of the entropy-based formulation $\epsilon_{MC4.0}$ as an alternative way of performing the initial steps of the energy-consumption what-if analyses. The usefulness of the proposed approach is demonstrated by comparing the results of a discrete-event simulation model of Mass Customization 4.0 environment (regarding the operating states of the system) and the values obtained by using the $\epsilon_{MC4.0}$

expression. The obtained results suggest that the $\epsilon_{MC4.0}$ expression acts as a fairly good trend indicator of the system's performance parameters increase/decrease and that the accuracy of the trend indicator depends on the mix of products processed by these manufacturing resources and the number of W_t and L_q decrease points associated with these products. This leads to the conclusion that there must be an optimal sequence of products that minimize the queue length Q_l and waiting time W_t normalized values or, in a worse case, stabilize these values around a desired level of performance. The recommendations for future research include the following:

- (1) Introducing a $\epsilon_{MC4.0}$ -based methodology to perform the energy-efficiency what-if scenarios, which, in turn, allow finding the most suitable and advantageous sequence of products to be processed by the manufacturing resources. Going back to Section 4.2, it can be noticed that, under some circumstances, Scenario #1 (sequential level of complexity) presents advantages compared to Scenario #2 (random level

of complexity), and vice versa. The proposed methodology could guide the process of finding the best alternative, according to a certain set of managerial objectives.

- (2) Assessing the validity of Cases #1 and #2—for identifying the W_t and Q_t decrease points within a certain sequence of products to be processed by the manufacturing resources—for the case of nonsequential manufacturing process routes. Going back to Table 2, it can be noticed that all the products presented follow sequential manufacturing process routes, meaning that the manufacturing flow always goes from M_1 to M_4 (something called flow dominance). The research question to be answered is whether Cases #1 and #2 are still valid for nonsequential manufacturing process routes, that is, $1M_4 + 2M_2$, $1M_1 + 2M_3 + 2M_1$, $1M_2 + 2M_4 + 2M_3 + 7M_1$, and so forth.
- (3) Exploring the impact the information-sharing mechanism—used to decide which type of product is more convenient to process next—has on the final W_t and Q_t values. Going back to Figure 2, it can be noticed that, in the information-sharing mechanism “machine-to-machine operation mode,” the main “interest” of a manufacturing resource is to choose a product with the highest number of compatible transformation operations. However, it could be the case of a hypothetical “product-to-product operation mode,” where the main “interest” of a product to be processed is to choose a manufacturing resource that guarantees minimum processing time.

Appendix

A

The discrete-event simulation (DES) model of the mass customization production system was developed based on the logic of the ARENA model “a Small Manufacturing System,” presented in [103], specifically with the use of the STATION and ROUTE modules (Figure 5 presents an excerpt of the DES model, for the case of manufacturing resource M_1). The simulation run output was verified and validated according to the recommendations proposed by [104]. A simulation runtime—long enough to allow the total processing of twelve units of each product type—was used, the system is assumed to be operating continuously, all processing times follow an exponential distribution, thirty replications were used for each scenario, and confidence intervals of 90% were used in order to provide the proper statistical basis for making inferences and conclusions.

Figure 2 refers to the machine-to-machine operation mode; each manufacturing resource drags to its waiting queue the type of product that is more convenient to be processed next. For example, M_{23} drags Product 2A1B1C from M_2 waiting queue (for the same reason expressed above) and M_2 proceeds in a similar way (dragging Product 1B from M_{23} waiting queue). In this case, products 5 and 6 were arbitrarily assigned priority of use in manufacturing

resources M_{14} , and M_{23} , respectively. The logic behind the machine-to-machine operation mode was that it was implemented based on the structure of the model “Service Model with Balking and Reneging,” presented in [103], specifically with the use of the SEARCH and REMOVE modules. Figure 6 presents an excerpt of the DES model for the case of manufacturing resources M_1 and M_{14} .

B

We exemplify how the calculations presented in this document were performed.

- (1) Regarding Table 4 (frequency of occurrence of alternative manufacturing process routes and related processing times: Scenario #1):
 - (i) For example, product 10 consumes two minutes of manufacturing resource M_1 , three minutes of M_2 , two minutes of M_3 , and nine minutes of M_4 :
 - (a) M_1 - M_2 - M_3 - M_4 route is followed 19.3% of the time
 - (b) M_1 - M_2 - M_{23} - M_4 route is followed 1.9% of the time
 - (c) M_1 - M_{23} - M_4 route is followed 26.2% of the time
 - (d) M_{14} - M_2 - M_3 route is followed 14.0% of the time
 - (e) M_{14} - M_2 - M_{23} route is followed 11.3% of the time
 - (f) M_{14} - M_{23} route is followed 27.3% of the time
 - (ii) The total consumed time by manufacturing resource is as follows:
 - (a) M_1 is $2 * (0.193 + 0.019 + 0.262) = 0.948$
 - (b) M_2 is $3 * (0.193 + 0.019 + 0.14 + 0.113) = 1.397$
 - (c) M_3 is $2 * (0.193 + 0.14) = 0.667$
 - (d) M_4 is $9 * (0.193 + 0.019 + 0.262) = 4.264$
 - (e) M_{14} is $(2 + 9) * (0.14 + 0.113 + 0.273) = 5.788$
 - (f) M_{23} is $2 * (0.019 + 0.113) + (3 + (2) * (0.262 + 0.273)) = 2.937$
 - (iii) The total combined time consumed is as follows:
 - (a) M_1 and M_4 must be equal to $(2 + 9) = 11$ minutes, which is confirmed by adding 0.948 (from M_1) + 4.264 (from M_4) + 5.788 (from M_{14})
 - (b) The total combined time consumed by M_2 and M_3 must be equal to $(2 + 3) = 5$ minutes, which is confirmed by adding 1.397 (from M_2) + 0.667 (from M_3) + 2.937 (from M_{23})
- (2) Regarding Table 5 (probabilities P_i for all the ten tested scenarios):
 - (i) row “Processing time on M_1 ” (from Table 4) shows the processing time consumed by manufacturing resource M_1 for each product; that is,

- (a) products 1 and 2 (Scenarios 1 and 2) do not use manufacturing resource M_1 (so it appears as NA)
 - (b) product 3 (Scenario 3) consumes 0.989 minutes
 - (c) product 4 (Scenario 4) consumes 2.881 minutes and so on
- (ii) row “ Σ processing time” shows the accumulated time for each scenario; that is,
- (a) products 1 and 2 do not use manufacturing resource M_1 , and the accumulated time is zero
 - (b) the accumulated time for product 3 is 0.989
 - (c) the accumulated time for product 7 is 3.87 and so on
- (iii) rows P_1 through P_{10} , Scenario 10, show the calculations for each product’s probability; that is,
- (a) product 1: $P_1 = \text{NA}/0 = \text{NA}$
 - (b) product 2: $P_1 = \text{NA}/0 = \text{NA}$ and $P_2 = \text{NA}/0 = \text{NA}$
 - (c) product 3: $P_1 = \text{NA}/0.989 = \text{NA}$, $P_2 = \text{NA}/0.989 = \text{NA}$, and $P_3 = 0.989/0.989 = 1$
 - (d) product 7: $P_1 = \text{NA}/3.87 = \text{NA}$, $P_2 = \text{NA}/3.87 = \text{NA}$, $P_3 = 0.989/3.87 = 0.2556$, $P_7 = 2.881/3.87 = 0.7444$, and so on
- (3) Regarding Table 6 ($\varepsilon_{\text{MC}4.0}$ values for manufacturing resource M_1 , Scenario #1):
- (i) rows P_1 through P_{10} , Scenario 10, show the calculations for each product’s $\varepsilon_{\text{MC}4.0}$ values, using equation (1) (it must be noted that whenever the processing time of a product i appears as NA, its associated P_i is considered to be NA, and its contribution to the $\varepsilon_{\text{MC}4.0}$ expression value is considered to be zero); that is,
 - (a) product 1: $\varepsilon_{\text{MC}4.0} = (1/\text{NA}) * \log_2(1/\text{NA}) = 0$
 - (b) product 2: $P_1 \ \varepsilon_{\text{MC}4.0} = (1/\text{NA}) * \log_2(1/\text{NA}) = 0$ and $P_2 \ \varepsilon_{\text{MC}4.0} = (1/\text{NA}) * \log_2(1/\text{NA}) = 0$
 - (c) product 3: $P_1 \ \varepsilon_{\text{MC}4.0} = (1/\text{NA}) * \log_2(1/\text{NA}) = 0$, $P_2 \ \varepsilon_{\text{MC}4.0} = (1/\text{NA}) * \log_2(1/\text{NA}) = 0$, and $P_3 \ \varepsilon_{\text{MC}4.0} = (1/1) * \log_2(1/1) = 0$
 - (d) product 7: $P_1 \ \varepsilon_{\text{MC}4.0} = (1/\text{NA}) * \log_2(1/\text{NA}) = 0$, $P_2 \ \varepsilon_{\text{MC}4.0} = (1/\text{NA}) * \log_2(1/\text{NA}) = 0$, $P_3 \ \varepsilon_{\text{MC}4.0} = (1/0.2556) * \log_2(1/0.2556) = 7.702$, $P_7 \ \varepsilon_{\text{MC}4.0} = (1/0.7444) * \log_2(1/0.7444) = 0.5719$, and so on

The last row in Table 6 (Calculated $\varepsilon_{\text{MC}4.0}$ for M_1) is the summation of each product’s $\varepsilon_{\text{MC}4.0}$ values. The reason for proceeding in this way has to do with the blocking effect the set of resources used for obtaining a product (and the sequence in which they are used) imposes on the process flow. More details about this blocking effect can be found in [98, 99].

C

Figure 7 shows, on the right side, the behavior of manufacturing resource M_2 (W_t , L_q , and $\varepsilon_{\text{MC}4.0}$ normalized values) and, on the left side, the products involved in Scenario #1 in terms of their processing time and according to the sequence on which they appear; that is, product P_3 ($2M_1 + 2M_2 + 2M_4$) is preceded by P_2 ($4M_3 + 4M_4$) and is followed by product P_7 ($3M_1 + 3M_2 + 6M_4$). In this figure,

- (i) the horizontal arrow denotes the sequence of processing times through the four different manufacturing resources M_i ; that is, for product 1, it does not use M_1 and M_3 and uses M_2 and M_4 for three minutes
- (ii) the vertical arrow denotes the sequence of processing times for the same manufacturing resource M_i ; that is, for manufacturing resource M_1 , products 1 and 2 do not use M_1 , product 3 uses it for two minutes, product 7 uses it for three minutes, and so on
- (iii) the “+” sign denotes an increase in the processing time; that is, for the case of M_1 , going from product 2 to product 3, there is an increase from zero to two minutes
- (iv) the “-” sign denotes a decrease in the processing time; that is, for the case of M_1 , going from product 7 to product 4, there is a decrease from three to two minutes
- (v) the “x” sign denotes no change in the processing time; that is, for the case of M_1 , going from product 1 to product 2, there is no change, as it remains in zero minutes

Now, from Figure 7, it can be observed that whenever there is a decrease in the W_t and L_q values, this corresponds to one of the following cases:

- (i) Case #1 (Figure 8)
- (ii) Case #2 (Figure 9)

The validity of Case #1 and Case #2 was tested by running different scenarios, consisting in varying the number of processed products and their processing sequence. As a result of proceeding in this way, it was found that, 100% of the times, there was a decrease point, and, 78.7% of the times, it corresponded to the conditions presented in Case #1 and Case #2. Also, from the 100% of times when there was a decrease point, 85.3% of the times, Case #1 and Case #2 conditions identified it correctly. Now, the fact that these results are not enough to make the claim that the conditions presented in Case #1 and Case #2 are total and always valid must be stressed. In any case, more research is needed regarding this issue.

Going back to the use of the incoming/outgoing conditions of Cases #1 and #2, for the calculation of the final $\varepsilon_{\text{MC}4.0}$ values for each manufacturing resource M_i , the following steps must be followed:

Step 1. Identify the products with related W_t and L_q decrease points, for each manufacturing resource M_i . For the case of Scenario #1, we identify the following points:

- (i) Manufacturing resource M_1 (Figure 3(a)): Case #1 and Case #2 are not present
- (ii) Manufacturing resource M_2 (Figure 3(b)): Case #1, products P_4 , P_8 , and P_9 ; Case #2, product P_6
- (iii) Manufacturing resource M_3 (Figure 3(c)): Case #1, products P_3 , P_7 , and P_{10} ; Case #2, product P_5
- (iv) Manufacturing resource M_4 (Figure 3(d)): Case #1 and Case #2 are not present

Step 2. Calculate the $\varepsilon_{MC4.0}$ values for each manufacturing resource M_i , without taking into account the products identified in the previous step. Table 10 shows the probabilities P_i for M_2 —Scenario #1—and the corresponding calculated $\varepsilon_{MC4.0}$ values. It can be noticed that products 4, 8, 6, and 9 are not taken into account for this calculation.

Step 3. Calculate the final $\varepsilon_{MC4.0}$ values for each manufacturing resource M_i by proceeding in the following way:

- (1) Use the calculated $\varepsilon_{MC4.0}$ values of each manufacturing resource M_i (Step 2)
- (2) Use the “criteria for final $\varepsilon_{MC4.0}$ ” (shown in row #3, Tables 11–13) to discount the impact the products—associated with the W_t and L_q decrease points—have on the calculated $\varepsilon_{MC4.0}$ values (from here the term “final $\varepsilon_{MC4.0}$ values” is used)

Step 4. Calculate the $\varepsilon_{MC4.0}$ values for manufacturing resources M_{14} and M_{23} , without taking into account the products identified in Step 1, for each manufacturing resource M_{i-} and M_{-j} . Table 14 shows the probabilities P_i for M_{23} —Scenario #1—and the corresponding calculated $\varepsilon_{MC4.0}$ values. It can be noticed that products P_4 , P_8 , P_6 , and P_9 (from manufacturing resource M_2) and products P_3 , P_7 , P_5 , and P_{10} (from manufacturing resource M_3) are not taken into account for this calculation.

Step 5. Calculate the final $\varepsilon_{MC4.0}$ values for manufacturing resources M_{14} and M_{23} by proceeding in the following way:

- (1) Use the calculated $\varepsilon_{MC4.0}$ value of each manufacturing resource M_{ij} (Step 4)
- (2) Use the “criteria for final $\varepsilon_{MC4.0}$ ” (shown in row #3, Tables 15 and 16) to discount the impact the products—associated with the W_t and L_q decrease points—have on the calculated $\varepsilon_{MC4.0}$ values (from here the term “final $\varepsilon_{MC4.0}$ values” is used)

Data Availability

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

Conflicts of Interest

The author declares that there are no conflicts of interest.

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