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ORIGINAL PAPER

Manufacturing Operations Scheduling Based in a Multidimensional Sustainable Manufacturing Index (SMI_{ik})

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Abstract

Many essential human needs can only be satisfied through goods and services provided by industry. The products of industry form the material basis of contemporary living standards. All nations rightly require and aspire to efficient industrial bases to satisfy changing needs (Brundtland in U N Comm 4:300 [1]). This aspiration has led nations into a race for industrialization, and this race, as well recognized by the Bruntland Report (Our Common Future, 1987), requires the permanent use of raw materials, constant increases in productivity, and generation of material goods in large quantities which have imposed a very high economic cost, as well as a heavy burden of environmental impacts (Brundtland in U N Comm 4:300 [1]). This document presents a production scheduling proposal for a manufacturing system, based on the maximization of the sustainable manufacturing index (SMI_{ik}) of each of the products to be manufactured. This model manages to develop a utility function that integrates the main dimensions that make up sustainable business development, offering a broader criterion than just economic utility as an element for making the production decision of a manufacturing system. Furthermore, it restricts this function to product demand and the capacity of the production system. In addition, it determines the existing correlation between the sustainable development (SD) dimensions, leading to the decision taken to seek a favorable correlation between them. This model makes it possible to obtain a production sequence oriented to the prioritization of those products that offer a greater contribution to business sustainability, offering, to decision-maker, a novel and synergic option to production scheduling.

Keywords Sustainable manufacturing · Sustainability · Sustainable development · Scheduling

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Introduction

Sustainable manufacturing arises because of the global demand for industrial systems to adopt strategies that allow them to make their productive exercise an activity that generates economic efficiency, while at the same time leading them to evaluate the environmental and social objectives and impacts in the progress of manufacturing operations and technologies [2]. In this context, production scheduling emerges as one of the main activities of sustainable manufacturing, being responsible for determining the order and timing of execution of the tasks of the production system.

However, in the second half of the twentieth century and as a reaction to the Stockholm Conference of 1972, on which all authors agree as the origin of Sustainable Development as a term and idea [4–10], ways of materializing this concept began to be proposed and, by 1987, Barbier proposed this as a challenge in multidimensional terms, the aim of which is to achieve, simultaneously, economic, ecological, and social sustainability, including the acceptance of externalities and undesired results, derived from the relatively contradictory nature of these dimensions [11].

Already in 2001, the Gothenburg European Council, through its president Nicole Fontaine, began the task of shaping the different structures resulting from the many and varied conceptualizations of sustainable development (SD) to achieve a better understanding of its behavior, but above all, to be able to understand its elements. This is when he put forward the first conceptual approximations of a structure made up of what he called economic, social, and environmental dimensions, making them inseparable.

In 2015, Durán, Gogan, Artene, and Duran [12] presented what they consider to be the key components of SD, identifying them as the economic component, the ecological component, and the human component. They add that "development should be conceived as a multidimensional process, involving fundamental changes in social structures and institutions, aiming at accelerated economic growth, reducing inequality and eradicating poverty" (p.809) [12].

But the approach that is beginning to be taken to SD from a multidimensional perspective brings with it greater complexity, given each of the dimensions defined and their interrelation; and because of the preponderance of some over others, it is necessary to see it as the harmony (or harmonization) between multiple forces that permanently interact with the different biophysical systems of the planet and economic growth.

This harmony can be even better appreciated when we look at the underlying elements of the conditions that development must have when it is stated that it must be economically efficient, ecologically sustainable, socially equitable, democratically founded, geopolitically acceptable, and culturally diversified [13]. This means that the problem of development and its sustainability must be approached from a broader perspective that goes beyond the environmental one, a perspective that must include the human, the social, the political, the institutional, and the economic, as edges of a polyhedron.

As presented by Chica-Urzola and Mendoza [14], "the approach to SD as a harmonic polyhedron allows it to be conceived as a multidimensional structure which is integrated by clearly identifiable dimensions" (p.396) [14]. It is in this perspective that it can be forged as a harmonic polyhedron whose edges are formed by four structures composed of an equal number of dimensions. These structures are the socio-humanist dimension, the economic dimension, the institutional dimension, and the environmental dimension.

This SD construct uses the Socratic idea of holistic and synergy, a term coined in the nineteenth century by Émile Littré, as fundamental tools. In other words, an integrated interpretation of these dimensions implies applying a global and not a unidimensional interpretation [14].

In summary, it can be said that sustainable development as a multidimensional process is of great value to society since, as mentioned by Cantú Martinez [8]: "it allows meditation on the operational content of development and involves the search for points of coincidence between the disciplinary spheres—social, economic and environmental—that constitute it, together with the internalization and general understanding of maintaining, over time, an infrastructure and capital of social, economic and environmental order" (p. 90) [8].

Business Sustainability

Many essential human needs can only be satisfied through goods and services provided by industry. The products of industry form the material basis of contemporary living standards. This is why all nations rightly require and aspire to efficient industrial bases to meet changing needs [1]. The adoption of the Brundtland Report by international bodies has brought consequences for the global industrial sector. Some of these consequences have been identified by various authors, most notably those associated with regulatory and legislative pressures on manufacturing industries, and prevailing shifts in the pattern of consumer demand towards more sustainable products and practices [2]. Therefore, industrial organizations now suffer not only from internal pressure to achieve economic benefits but also from external pressures to establish a system of environmental and social responsibility [3].

Along the same lines, Accinelli and De La Fuente [15] argue that there is an apparent agreement in the literature regarding the existence of pressures that the organizational environment is exerting on companies to adopt a series of solutions aimed at protecting and conserving the natural environment, either through existing legislation or through market mechanisms, so that it is increasingly common to find companies that present themselves as socially responsible and environmentally aware of the impact that their activity has on the natural environment [15]. The manufacturing sector, which is the subject of this research, is no exception to this situation.

As a result, the current global focus is now to support and compel manufacturing industries to implement cleaner and more efficient production practices that enable the development of products and services with reduced negative environmental and social impacts [2, 16–18]. As Rosen and Kishawy [19] rightly put it, manufacturing industries are faced, in addition to economic efficiency, with evaluating environmental and social goals and impacts in advancing manufacturing operations, technologies, and competitive position [19].

About sustainable development, Baumgartner and Ebner [20] argue that it represents rising social expectations for business conduct, a perspective shared by the United Nations when presenting the Sustainable Development Goals (SDGs) as these are planned to act as framework conditions for the global economy in the coming years [21].

As Sikdar [22] argues, industrial companies are directly or indirectly responsible for environmental degradation, or at least a significant part of it. Sustainability in manufacturing systems is an increasingly important requirement for today's manufacturing companies due to several established and emerging causes: environmental concerns, diminishing non-renewable resources, stricter legislation, inflated energy costs, growing consumer preference for environmentally friendly products, and so on. [23].

When, in 1972, the Meadows Report (Limits to Growth) was published, it began to propose the need for a change in the model of resource consumption, since the linear model, based on inputs, transformation, and outputs, is only sustainable in the face of the infinite existence of resources. He does this in the face of what he calls the imminent depletion of resources if the prevailing model is not changed and the halt in industrial growth as a result [24].

This sentence set off alarm bells in the different sectors involved in and responsible for the production and consumption of the planet's resources. Especially when reflecting on the role of industry, which as recognized in the Brundtland Report (1987) "is fundamental to the economies of modern societies and an indispensable engine of growth" [1] (p. 173):

a. The nature of companies makes them those elements that take natural resources and transform them into finished products; thus, they are seen as the predators of natural resources [25, 26].
b. During the process of transformation of these raw materials and incoming inputs, the company generates by-products and emissions both liquid and solid, fumes, vapors, and aerosols whose impact on the environment is polluting [22, 27–29]. Manufacturing and industrial processes are also known to be important sources of greenhouse gas (GHG) emissions. Statistics have shown that GHGs emitted from the use of energy sources such as electricity, coal, oil, and gas during manufacturing account for more than 37%, even 50%, of the global GHG total [30].
c. Once the consumption cycle of the product by the user is over, it is disposed of inappropriately, causing stress at the disposal sites as the load received is often greater than the absorption rate of the planet, both in quantity and time [31–34].
d. Companies have been seen as places where economic growth is privileged to the detriment of the well-being of workers and the environment, often without applying compensation strategies to the territory or generating negative impacts on it [17, 18, 35, 36].
e. Lack of knowledge, confusion, or misunderstanding of what is meant by Corporate Sustainability or Corporate Sustainable Development. This is largely due to the enormous number of concepts and interpretations that have been made about Sustainable Development since this concept began to be used in the world. On the other hand, it is also due to the industrial sector's lack of interest in getting involved in this area [37–40].

In a complementary manner, as Chang and Cheng [41] rightly express, multiple authors have recognized that sustainable development provides competitive advantages over competitors [42, 43].

However, as Henao, Sarache, and Gómez [44] put it, this is easier said than done. Despite the wake-up call generated by the 1987 "Brundtland Report" of the United Nations World Commission on Environment and Development (WCED, 1987), evidence suggests that many companies continue to relegate environmental protection and social responsibility to places below or subordinate to economic performance [44].

In the same way, Gray and Bebbington [45] suggest that the evidence from research on these issues is that there is a conflict between corporate objectives and the attractiveness of sustainable development. It appears that good environmental performance or socially responsible behavior towards the natural environment and society on the part of business conflicts with the central objective of any company: profit maximization [15].

The link between manufacturing and its operations with the natural environment is gradually being recognized. Progress, profitability, productivity, and environmental protection are now considered aspects to be considered by manufacturing organizations [46].

As Morioka and de Carvalho [47] rightly put it, by orienting the company's activities with sustainable development, the organization matches its responsibilities to society and the environment at the institutional, organizational, and individual levels [47]. However, it is important to note that sustainability must urgently be considered at all levels, not only at the strategic level but also at the tactical and operational levels to have a complete transmission belt from global policies to operational activities [23].

Sustainable Manufacturing and Manufacturing Operations Scheduling

Sustainability has been applied to many fields, such as engineering, manufacturing, and design. Manufacturers are increasingly concerned with the issue of sustainability. For example, the recognition of the relationship between manufacturing operations and the natural environment has become an important factor in decision-making among industrial societies [19]. Thus, companies have started to take measures to reduce GHG emissions from their products and services under increasing pressure from the implementation of the Kyoto Protocol and the Copenhagen Protocol [48]. However, it is still difficult for companies to consider the use of renewable sources and emission reductions when making manufacturing and operational decisions, especially regarding the problem of production planning and scheduling [49].

More specifically, sustainable manufacturing requires balancing and integrating society's economic and environmental objectives, supporting policies and practices. Appropriate compromises often need to be made, given the diverse interests of manufacturers and society. In addition, organizations and their managers need to have relevant, meaningful, consistent, and robust information on sustainable manufacturing and use it to improve sustainability in manufacturing [19].

It is from the different business visions of sustainable development that corporate sustainability performance has come to be defined in many ways. One of these is the definition of sustainable manufacturing, which is defined as "the creation of manufactured products through economically rational processes that minimize negative environmental impacts while conserving energy and natural resources. Sustainable manufacturing also improves employee, community and product safety." [49, 50], while the Lowell Center for Sustainable Production defines sustainable production as "the creation of goods and services using processes and systems that are non-polluting, energy and natural resource conserving, economically viable, safe and healthy for workers, communities, and consumers, socially and creatively rewarding for all workers" [19]. But if there is one thing, they all converge on, it is to approach it as a strategy for companies to seek harmony between economic profit, environmental and social responsibility, and other stakeholders [3].

From this convergence on how sustainable manufacturing can be defined, the main ways of operationalizing this conceptualization emerge [51]:

a. Manufacturing for sustainability, which refers to the elaboration of products to help society to be sustainable; within this category, we can identify tools such as sustainable design, green logistics, carbon footprint, water footprint, circular economy, and product life cycle, among others.
b. Manufacturing sustainability, which refers to the production of products through a sustainable production system. These include initiatives and tools such as sustainable manufacturing and S-ERP, among others.

The importance of companies adopting sustainable manufacturing measures and strategies is increasingly recognized. The IPCC sixth assessment report [52] further reinforces that climate change is caused by anthropomorphic activities and can have very serious consequences while pointing out that resources (e.g., energy, materials, water) critical to the development of manufacturing activities are now considered to be subject to scarcity and, in many cases, non-renewable, which can affect operations.

Production, seen from a management perspective, is composed of three (3) activities: planning, scheduling, and manufacturing control. Planning consists of identifying the strengths of the business system and comparing them with the opportunities in the environment to determine a strategy that will enable it to deal with them in the best possible way. On the other hand, production scheduling is the allocation of resources (human and technical) to specific tasks in specific periods, and in this way, it materializes the production plan [53]. Production control is a transversal function of planning and scheduling production. Figure 1 shows the structure of production function from the management perspective.

Production scheduling involves decision-making at the tactical and operational level on the shop floor and this involves not only the manufacturing stage of the product life cycle but also the operational stage of the processes. Manufacturing operations management, and especially scheduling in manufacturing, is one of the most studied problems in the operations research and control communities [23].

Sustainable manufacturing from a multidimensional perspective, derived from approaching sustainable business development from a multidimensional view that includes the economic, environmental, and social pillars, has been introduced to holistically assess the performance of a manufacturing company. Despite the importance of sustainable manufacturing research, there is virtually no holistic model that considers all three pillars for sustainable manufacturing programming [54].

Mathematical Model

For the application of the developed model, we will start from the assumption of a job-shop-MTO (make-to-order) manufacturing environment. In this type of production system, work is carried out according to the needs of the customer, who activates

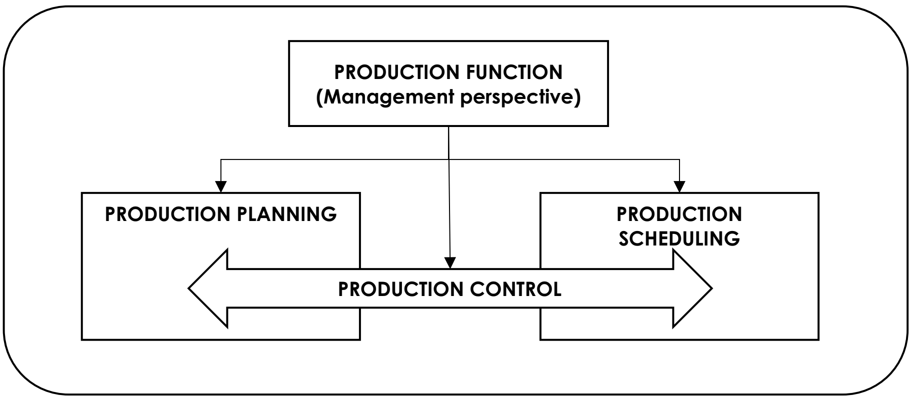

Fig. 1 Structure of production function from the management perspective

production when a demand or order is issued. This type of dynamic is known as pull manufacturing systems. Given the unique or highly customized characteristics of each order, it is especially difficult to manage final product inventory, which exposes companies with a make-to-order manufacturing environment to a critical level of demand response and difficulties in meeting delivery dates [55–57].

Other elements on which the assumption of the manufacturing environment of this application is based are assumptions such as the following: (a) all jobs or orders are known in the period $t=0$; (b) the set-up times of the working means are negligible; (c) the transport times between machines are not relevant and therefore are not considered; (d) it is not possible to partition batches; (e) there is no single production route as this depends on each product.

Another key assumption for the construction of the model is that there are costs associated with each of the dimensions of sustainable development (economic, environmental, and social) that are taken into account. These costs are specified per unit of output. However, there are a variety of methods to estimate the costs associated with the manufacturing process; these methods can be classified into three (3) large groups, analogy cost estimation, parametric cost estimation, and activity-based costing estimation, although combinations of these can also be presented [58].

The mathematical model aims at maximizing the overall sustainable utility of the production system (1), which is aggregated into a sustainable manufacturing index (SMI_{ik}), multiplied by the quantities of each product to be produced in each of the production periods (X_{ik}).

In turn, this objective function is constrained by a set of mathematical expressions that limit it. The first (2) restricts total production to the available capacity of the production system in each period. The second (3) restricts production to the demand for each product in each period, seeking to ensure that the due commitment is satisfied.

Then, expression (4) seeks to determine the harmony condition of the SD dimensions by calculating Pearson's correlation coefficient, called SR_{ik}, as an indicator of the sense and intensity of the relationships between the dimensions.

In addition, identities are formulated:

a. The sustainable manufacturing index (SMI_{ik}) is the difference between the aggregate income of the dimensions of sustainable development (economic, social, and environmental) of each product and the cost caused by the product in the same dimensions (6).
b. Another set of identities defines the revenue generated by the product in each of the dimensions of sustainable development as the cost caused by the product plus the percentage of profit to be made, as determined by the organization (7), (8), (9), (10), and (11).
c. We also present the identity that allows us to calculate the available capacity of the production system per period of the horizon subject to planning and programming (12), understood according to what is expressed by [59] as that with which the companies work, since it is equivalent to the number of hours available to carry out the production task after having discounted the hours corresponding to the maintenance times of the means of work and the time losses due to organizational and unforeseen factors.
d. Expression (13) shows how to determine the value of the SR_{ik}, which is the correlation coefficient calculated between the different dimensions evaluated. For its calculation, it is necessary to previously determine the expression corresponding to the SI_{kd}: (14) or income obtained by the sustainability of the product, which is nothing more than a set

of matrices, one for each dimension, where the elements that make it up are the result of the quotient between the income of the product for each of the dimensions between the income obtained by the dimension corresponding to the calculated matrix.

The overall utility of the system, in terms of sustainability, is understood as the difference between the income of each product and its cost, but both elements are expressed in terms of the sustainability of the product, a function that relates the subcategories of sustainable manufacturing presented by [51] and expanded by Chica and Serna [60].

In this framework, the mathematical model proposed is:

$$\text{Max } F(\text{Xik}) = \sum_{\text{i}=1}^{\text{n}} \sum_{\text{k}=1}^{\text{T}} \text{SMI}_{\text{ik}} X_{\text{ik}}, \tag{1}$$

s.t.

$$\sum_{\text{i}=1}^{\text{n}} \text{PT}_{\text{ijk}} X_{\text{ik}} \leq \text{AC}_{\text{jk}} \quad ;\forall j = 1, \dots, m \;\; ;\forall k = 1, \dots, T \;\; , \tag{2}$$

$$X_{\text{ik}} \leq D_{\text{ik}} \;\; ;\forall i = 1, \dots, n \;\; ;\forall k = 1, \dots, T, \tag{3}$$

$$-1 < \text{SR}_{\text{kd}} \leq 1 \;\; ;\forall d = 1, \dots, D \;\; ;\forall k = 1, \dots, T, \tag{4}$$

$$\forall X_{\text{ik}} \geq 0. \tag{5}$$

In addition:

$$\text{SMI}_{\text{ik}} = \text{SP}_{\text{ik}} = \left(\text{DI}_{\text{ikd}}\right) - \left(\text{DC}_{\text{ikd}}\right), \tag{6}$$

$$\text{DI}_{\text{ikd}} = \left(\text{EI}_{\text{ik}} + \text{SoI}_{\text{ik}} + \text{Ev}_{\text{ik}}\right), \tag{7}$$

$$\text{DC}_{\text{ikd}} = \left(\text{EC}_{\text{ik}} + \text{SoC}_{\text{ik}} + \text{Ev}_{\text{ik}}\right), \tag{8}$$

$$\text{EI}_{\text{ik}} = \text{STC}_{\text{ik}} \times \left(1 + \text{PSTC}_{\text{ik}}\right), \tag{9}$$

$$\text{SoI}_{\text{ik}} = \text{SoC}_{\text{ik}} \times \left(1 + \text{PSoC}_{\text{ik}}\right), \tag{10}$$

$$\text{EvI}_{\text{ik}} = \text{EvC}_{\text{ik}} \times \left(1 + \text{PEvC}_{\text{ik}}\right), \tag{11}$$

$$\text{AC}_{\text{jk}} = \left[(\text{BD}_{\text{k}}) \times \left({}^{\text{WH}_{\text{k}}}/_{\text{d}} \right) \times \left({}^{\#S_{\text{k}}}/_{\text{d}} \right) \times (n_{\text{jk}})\right] - \left[G_{1\text{k}} + \left(\frac{G_{2\text{k}} + G_{3\text{k}} + G_{4\text{k}}}{N_{\text{jk}}}\right) \times n_{\text{jk}}\right], \tag{12}$$

$$\text{SR}_{\text{kd}} = \rho_{\text{kd;kd+1}}\left(\frac{\text{Cov}(\text{SI}_{\text{kd}};\text{SIk}_{\text{d+1}})}{\sqrt{\text{Var(kd).Var(kd+1)}}}\right) \;;\rho_{\text{kd;kd+2}}\left(\frac{\text{Cov}(\text{SI}_{\text{kd}};\text{SI}_{\text{kd+2}})}{\sqrt{\text{Var(kd).Var(kd+2)}}}\right) \;\; ;\dots \;\; ;\dots ;\rho_{\text{kd;kD}}\left(\frac{\text{Cov}\left(\text{SI}_{\text{kd}};\text{SIk}_{\text{D}}\right)}{\sqrt{\text{Var(kd).Var(kD)}}}\right), \tag{13}$$

$$SI_{kd} = \begin{pmatrix} \frac{EI_{1k}}{EI_{1k}} & \frac{SoI_{1k}}{EI_{1k}} & \frac{EvI_{1k}}{EI_{1k}} \\ \vdots & \vdots & \vdots \\ \frac{EI_{nk}}{EI_{nk}} & \cdots \frac{SoI_{nk}}{EI_{nk}} & \frac{EvI_{nk}}{EI_{nk}} \end{pmatrix}; \begin{pmatrix} \frac{EI_{1k}}{SoI_{1k}} & \frac{SoI_{1k}}{SoI_{1k}} & \frac{EvI_{1k}}{SoI_{1k}} \\ \vdots & \vdots & \vdots \\ \frac{EI_{nk}}{SoI_{nk}} & \cdots \frac{SoI_{nk}}{SoI_{nk}} & \frac{EvI_{nk}}{EI_{nk}} \end{pmatrix}; \begin{pmatrix} \frac{EI_{1k}}{EvI_{1k}} & \frac{SoI_{1k}}{EvI_{1k}} & \frac{EvI_{1k}}{EvI_{1k}} \\ \vdots & \vdots & \vdots \\ \frac{EI_{nk}}{EvI_{nk}} & \cdots \frac{SoI_{nk}}{EvI_{nk}} & \frac{EvI_{nk}}{EvI_{nk}} \end{pmatrix}, \tag{14}$$

where:

i	product type i ($i = 1, 2, \ldots, n$)
j	machine type j ($j = 1, 2, \ldots, m$)
k	production period k of the planning and scheduling horizon ($k = 1, 2, \ldots, T$)
d	sustainable development dimension ($d = 1, 2, \ldots, D \approx d =$ economic (E), social, (So) environmental (Ev)…, D)
X_{ik}	quantity of product i to be manufactured in k period
SMI_{ik}	sustainable manufacturing index from product i in k period
PT_{ijk}	processing time of product i in machine j in k period
AC_{jk}	available capacity of machine j in k period
D_{ik}	demand (order quantity) of product i in k period
SP_{ik}	sustainable profit of product i in k period
DI_{ikd}	dimensional income of product i in k period from dimension d
DC_{ikd}	dimensional cost of product i in k period from dimension d
EI_{ik}	economic income of product i in k period
SoI_{ik}	social income of product i in k period
EvI_{ik}	environmental income of product i in k period
EC_{ik}	economic cost of product i in k period
SoC_{ik}	social cost of product i in k period
EvC_{ik}	environmental cost of product i in k period
STC_{ik}	standard cost per unit of product i in k period
$PSTC_{ik}$	profit percentage over standard cost per unit of product i in k period
$PSoC_{ik}$	profit percentage over social cost per unit of product i in k period
$PEvC_{ik}$	profit percentage over environmental cost per unit of product i in k period
BD_K	business days per k period
WH_k/d	working hours per work shift in k period/day.
$\#S_k/d$	number of shifts per day in k period
N_{jk}	total number of machines in k period ($N_{jk} = \sum_{j=1}^{m} n_{jk}; \forall k = 1, 2, \ldots, T$)
n_{jk}	number of type j machines in k period
G_{1k}	total maintenance times for each type j machine in k period ($G_{1k} = \sum_{j=1}^{m} g_{jk}; \forall k = 1, \ldots, T$)
g_{jk}	maintenance times for each type j machine in k period.
$G_{2k} + G_{3k} + G_{4k}$	loss of time due to work absenteeism, administrative and unforeseen problems in the period k
SR_{ik}	sustainable ratio from dimension d in k period (Pearson coefficient)
SI_{kd}	sustainable income from dimension d in k period

This model is presented for application in pull-type manufacturing production systems. In this system, production is limited to the demand determined for the model as far as the capacity of the system allows. If an infectibility is generated in terms of demand parameters, a capacity expansion strategy is established using scheduling overtime, renting spare capacity from another production system, maquila, or any other associated modality, or the spare production could be purchased from another company with a strategic alliance.

However, the model was conceived for production systems under a job-shop-type configuration, but this consideration does not rule out its application in flow-shop-type systems, although for these systems, it is necessary to consider the need to increase the capacity of one or more means of work in order to comply with the demand restriction inherent to MTO systems.

Similarly, it is estimated that this model can be applied to push or MTS systems, although the latter were not initially assessed, due to the consideration of sustainability offered by MTO systems in terms of responsible consumption, as they are not designed to generate large volumes of inventory.

As for the application of this mathematical model to other productive sectors, other than manufacturing, this was not considered, although it is not ruled out if the variables and restrictions can be adapted to these sectors.

Production Scheduling Maximizing Sustainability

To solve the mathematical model of the previous section and generate the expected results of production scheduling, the "SC_{ik}: sustainability coefficient of product *i* in period *k*" is determined for each product as follows:

$$SC_{ik} = \frac{SMI_{ik}}{PT_{ij*k}}, \tag{15}$$

where:

SC_{ik} sustainable coefficient of product *i* in *k* period
PT_{ij*k} processing time of product *i* in machine *j** in *k* period
*j** capacity restrictive resource (bottle neck machine)

The production sequence is generated by ordering from the highest to the lowest value obtained in the SC_{ikp} for each product, as follows:

$$\text{Production sequence } \left(PS_k\right) : SC_{ik1} > SC_{ik2} > SC_{ik3} >_{\ldots} > SC_{ikp} \tag{16}$$

where:

PS_k production scheduling of *k* period
SC_{ikp} sustainable coefficient of product *i* positioned in sequency position *p* in *k* period
p sequency position or production order in production grid

In this way, the production scheduler or scheduling decision-maker determines the sequence of dispatching the different pending orders in the production grid, ensuring that those jobs with the highest sustainability coefficient are the first to be scheduled and carried out, taking advantage of the capacity of the manufacturing system, and dispatching at the end of the sequence those products whose contribution to sustainability is the lowest.

Table 1 Economic information

Product (i)	Demand, D_{ik} (u/w)	STC_{ik} ($/u)	$PSTC_{ik}$ (%)	SoC_{ik} ($/u)	$PSoC_{ik}$ (%)	EvC_{ik} ($/u)	$PEvC_{ik}$ (%)
A	10	$2.80	10%	$0.50	15%	$1.70	10%
B	12	$1.50	15%	$3.00	8%	$5.00	15%
C	15	$1.80	18%	$2.20	12%	$3.00	18%

u/w, units per week; *$/u*, dollars per unit

Table 2 Production information

Machine (j)	Quantity	g_{jk} (h/w)	PT_{ijk}, product (i) (h/u)		
			A	B	C
M1	1	2	1.00	1.00	1.00
M2	1	1	1.00	2.00	1.00
M3	1	3	1.00	3.00	2.00
BD_k (d/w)	WH_k/d	$\#S_k$/d	G_{2k} (h/w)	G_{3k} (h/w)	G_{4k} (h/w)
5	8	2	5	1	3

d/w, days per week; *h/w*, hours per week; *h/u*, hours per unit

Results and Discussion

As mentioned in the "Sustainable Manufacturing and Manufacturing Operations Scheduling" section, sustainable manufacturing can be classified, according to the strategies used, into two (2) groups: manufacturing for sustainability and sustainability of manufacturing. In the case of the mathematical model proposed and its development and application in production systems, use is made of these two classifications by means of two (2) different basic assumptions:

i. Manufacturing for sustainability: use is made of the MTO strategy, which aims to limit the quantity of product manufactured by limiting it to demand, avoiding the generation of unnecessary and/or excessive inventories, while encouraging the responsible consumption of products by limiting supply.
ii. Manufacturing sustainability: this form of sustainable manufacturing is achieved through the application of a mathematical model, which aims to prioritize production according to the SMI_{ik} and to determine its order in the production grid based on its SC_{ik}.

In addition to the above, with the calculation of the SR_{ik}, an element is introduced that allows balancing the different dimensions of the SD by identifying the relationship present between them.

Now, with all the above as a framework, a case of application of the model and its form of development is presented. Assume that you have a business system that manufactures three products. The economic information is shown in Table 1.

The production information is shown in Table 2.

Based on the information in Table 2 and using the expression (12), the available capacity of each of the machines (Mj) is determined. This result is shown in Table 3.

With the information in Tables 1, 2, and 3, the values of expressions 6, 7, 8, 9, 10, 11, and 16 are determined. This is shown in Table 4.

The sequence of production is thus organized as follows: B, C, A. The results of the production schedule are presented in Table 5.

Of the demand for product A, it cannot be fully realized due to the lack of capacity of the working means *j**. This implies that the business system must develop a strategy to obtain the missing units and fulfill the entire commitment.

However, in order to determine the sustainable ratio (SR_{dk}) for each of the dimensions of sustainable development, it is first necessary to construct the income matrices for each of the dimensions evaluated, according to expression (14). Table 6 shows the matrices for each of the dimensions considered, the economic dimension, the social dimension, and the environmental dimension for each of the products to be manufactured.

Table 3 Available capacity

Machine (j)	AC_{jk} (h/w)
M1	75
M2	76
M3	74

*j** = M3

h/w, hours per week

Machine 3 (M3) becomes the constraining capacity resource (*j**)

Table 4 Sustainable coefficient (SC_{ik}) and production scheduling (PS_k)

Product (*i*)	EI_{ik} ($/u)	SoI_{ik} ($/u)	EvI_{ik} ($/u)	SMI_{ik} ($/u)	SC_{ik} ($/u-hj*)	PS_k
A	$3.08	$0.58	$1.87	$0.53	$0.53	3
B	$1.73	$3.24	$5.75	$1.22	$0.41	1
C	$2.12	$2.46	$3.54	$1.13	$0.56	2

*$/u-hj**, dollars per unit per processing hour in *j**

Table 5 Productions results

Product (*i*)	Demand, D_{ik} (u/w)	RC_{j*k} (h)	MU_i (u)	UAC_{j*k} (h/w)	RAC_{j*k} (h/w)	PUM_{ik} (u)	NAC_{j*k} (h/w)
B	12	36	12	36	38	0	0
C	15	30	15	30	8	0	0
A	10	10	8	8	0	2	2

RC_{j*k}, required capacity for production in machine *j** in *k* period

MUi, manufactured units of product *i*

UAC_{j*k}, used available capacity of *j** in *k* period

RAC_{j*k}, remaining available capacity of *j** in *k* period

PUM_{ik}, pending units to be manufactured of product *i* in *k* period

NAC_{j*k}, need for expansion of available capacity of *j** in *k* period

Table 6 Sustainable income—SI_{dk}

EI_{ik}			SoI_{ik}			EvI_{ik}		
1.00	0.19	0.61	5.36	1.00	3.25	1.65	0.31	1.00
1.00	1.88	3.33	0.53	1.00	1.77	0.30	0.56	1.00
1.00	1.16	1.67	0.86	1.00	1.44	0.60	0.70	1.00

With these matrices constructed, the covariance is calculated for each of the possible combinations (pairs) of dimensions assessed. The covariance indicates whether the pairs of associated dimensions vary in the same direction (positive covariance) or in the opposite direction (negative covariance). There is no significance in the numerical value of covariance; only the sign is useful. After calculating the covariance, the Pearson correlation coefficient (sustainable ratio—SR_{dk}) is calculated, according to expression (13); this correlation coefficient varies between -1 and $+1$. If the correlation value is 0, it means that there is no linear relationship between the variables; however, another functional relationship may exist.

The covariance provides the direction (positive, negative, close to zero) of the linear relationship of the analyzed pair of dimensions, while the correlation contains the intensity of this relationship. Table 7 shows the results of the covariance and Pearson's coefficient for the possible combinations of ordered pairs of the dimensions assessed.

Thus, it is observed that there is a negative covariance between the economic and social dimensions (EI_{ik}–SoI_{ik}) indicating that there is a linear relationship between them in the opposite direction. Between the social and environmental dimensions (SoI_{ik}–EvI_{ik}) and the economic and environmental dimensions (EI_{ik}–EvI_{ik}), there is a relationship in the same direction, i.e., a positive relationship.

Now, when we look at the result of the correlation coefficient or sustainable ratio, we can see $-1 < \rho EI_{ik}–SoI_{ik} < 0$, which means that the correlation between the two variables is negative; therefore, when one variable increases, the other decreases. However, it can also be seen that the value of this is close to 0 and this can be interpreted as a very weak correlation between these two dimensions. This does not mean that the variables are independent, as they could have a non-linear relationship.

The correlations between the other ordered pairs of dimensions show positive values ($0 < \rho SoI_{ik}–EvI_{ik} < 1$ and $0 < \rho EI_{ik}–EvI_{ik} < 1$); this indicates that the correlation between the two variables is positive, i.e., one variable tends to increase its value when the other also increases. Now, the coefficient between the economic and social dimensions (SoI_{ik}–EvI_{ik}), in addition to having a positive value as mentioned above, has a high value (close to $+1$); the closer the value is to $+1$, the stronger the relationship between the variables.

In other words, when the relationship between EI_{ik}–SoI_{ik} is observed, it can be said that it is linear and inverse in nature (because the value found is negative) and, in addition to this, it is a weak relationship (this is derived from the fact that the value obtained in the correlation between these variables is close to 0). With these elements, it can be inferred that, when the economic dimension obtains a positive increase (EI_{ik}), the social dimension

Table 7 Sustainable ratio—SR_{kd}

	EI_{ik}–SoI_{ik}	SoI_{ik}–EvI_{ik}	EI_{ik}–EvI_{ik}
Covariance	−0.132	0.58915	0.09058
Pearson coefficient ($\rho_{kd;\ kd+1;\ kd+2;\ kD}$)	−0.0935	0.89536	0.2352

(SoI_{ik}) presents a reduction proportional to the increase in the economic dimension. For example, an increase in the profit margin on the product (resulting from an increase in the selling price) would have a proportional reduction in the number of people who could have access to the product and thus satisfy their need.

Similarly, the relationship between the social and environmental dimensions (SoI_{ik}–EvI_{ik}) and the economic and environmental dimensions (EI_{ik}–EvI_{ik}) both has positive values. This indicates that their relationship (between the analyzed pairs) is linear and direct and that, although it is not very strong in the case of EI_{ik}–EvI_{ik}, it is strong in the case of the pair SoI_{ik}—EvI_{ik}. This can be best interpreted with the following example: an improvement in the environmental dimension (EvI_{ik}) could be derived from the feeling of contributing to a healthier environment and enjoying it by building social fabric, or from the increase in the generation of indirect employment derived from the need for more recyclable material recyclers. In the same way, this same increase in the environmental dimension (EvI_{ik}) could lead to an increase in the economic dimension (EI_{ik}) derived from the increase in the product's profit margin, because of the reduction in production costs derived from the recycled raw materials.

The importance of the sustainable ratio (SR_{kd}) lies in the possibility of establishing a measure of the direction and intensity of the correlations between the dimensions of sustainable development and, based on these elements, orienting actions, and decisions towards harmony (or harmonization) of these and, as Chica-Urzola and Serna (2018) put it, building a polyhedral business structure that is harmonious with the dimensions of sustainable development [14].

Now, both the mathematical model presented and the methodology proposed for its solution have been designed so that the decision-maker can include business sustainability as one of the organizational objectives and carry out a production scheduling according to this purpose.

Once this objective has been determined, the production scheduler makes the decision to decide the production sequence applicable to the grid of pending production orders and, with the sequence determined, carries out the floor scheduling resulting from the execution of this sequence.

Conclusions

This proposed methodology for production scheduling for a manufacturing system starts from the possibility of the business system to make a complete identification, evaluation, and determination of the economic, social, and environmental costs caused by its productive activity. In addition to this, it establishes the possibility of generating a profit margin on each of these cost elements.

Another important element of the mathematical model is the possibility of including the variable "time or period," i.e., it is not a static model but contemplates the possibility of changes in the values of the variables derived from the dynamics of the environment.

The results generated are constrained by the capacity constraint resource (j^*) which allows integrating this production scheduling methodology with the theory of constraints (TOC) and making use of many elements of the latter to complement it.

The development of a sustainable manufacturing index (SMI_{ik}) has many advantages: measuring product sustainability, prioritizing the use of work resources to maximize corporate sustainability, establishing a sustainability-oriented accounting system, a multidimensional approach to manufacturing sustainability, among others.

Given that the methodology for the development of the mathematical model has as a restriction the capacity of the means of work, there is the possibility that this may not be sufficient to be able to meet the entire committed demand for the products. In these cases, the methodology makes it possible to determine what fraction of the demand cannot be realized due to a lack of capacity and offers the production system the possibility of making decisions regarding this: increasing capacity, outsourcing, rescheduling orders, etc.

Also, by means of the sustainable ratio (SR_{ik}) or Pearson's correlation coefficient, it is intended to provide a measure of the correlation and harmony in the development of the dimensions of sustainable development evaluated, so that the industrial system can make decisions related to the impact on each one of them and thus be able to harmonize these interrelationships.

The proposed methodology aims to orient production programming and, in essence, the productive exercise towards those products that have a high sustainability coefficient, i.e., that contribute to business sustainability to a greater extent and discourages business attrition in products with low contributions to sustainability.

As observed in the sections of "Mathematical model" and "Results and discussion," this model can be applied in manufacturing systems with job-shop or flow-shop production configuration and with an MTO purpose, considering possible adjustments in capacity, derived from expansion needs to meet the projected demand and the production sequence generated. This gives rise to a future line of research, which consists of the evaluation of this model in production systems with MTS objectives or other economic sectors, such as services, agriculture, or commodities.

Currently, the models that allow production scheduling and obtain the product production sequence are based on objectives such as maximizing the economic utility of the system, minimizing the production time, and minimizing latency or delays in deliveries to the customer or scheduling based on priorities, among others. This model makes it possible to obtain a production sequence oriented towards the prioritization of the manufacture of those products that offer a greater contribution to business sustainability, adjusting the capacity of the system to this sequence and providing the decision-maker with the opportunity to know the relationship that, in terms of sustainability, exists between the dimensions of the DS and to design strategies that allow a positive balance to be obtained from these correlations.

This constitutes a competitive advantage for those manufacturing systems that make use of the model as a tool to make the production scheduling decision since there are no other models for scheduling production and determining the sequence of production of the products, whose objective is the sustainability of the manufacturing system.

Author Contribution The author realized the study conception and design; conceptualization; methodology; formal analysis and investigation; writing—original draft preparation; writing—review and editing material preparation; data collection and analysis; wrote, read, and approved the final manuscript.

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Data Availability The data that support the findings of this study are available (anonymized) from the corresponding author, upon reasonable request.

Declarations

Ethics Approval and Consent to Participate Not applicable.

Consent for Publication Not applicable.

Conflict of Interest The author declares no competing interests.

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