An Integrated Product Development Approach to Improving Sustainability Using Simulated Experiments: Manufacturing Case Study

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Abstract Sustainable Manufacturing (SM) and Integrated Product Development (IPD) have both been identified as important drivers of an organization's competitiveness and agility. However, their multi-faceted nature requires organizations to make manufacturing decisions without compromising any of the pillars contained within SM (economy, environment and society) and IPD (product, production and business). Achieving the aims of both IPD and SM increases this complexity even further and results in the need for high-level tools and systems for decision-making. This paper presents the use of digital factory simulation, as a tool to support the integrated development of sustainable products and processes. To evaluate this approach, a case study involving an existing manufacturing line was performed. The aim of the study was to generate a platform for the testing of experimental scenarios giving predictive results on the impact of IPD decisions on the manufacturing sustainability of the process. Together with the limitations and difficulties encountered, the validity and feasibility of using digital factory simulation for the integrated development of sustainable products and processes is discussed.

Keywords Sustainable manufacturing · Integrated product development · Simulation

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1 Introduction

In 1987, The World Commission on Environment and Development defined Sustainable Development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [1]. Also, in 1987, Barbier suggested that any process of development will have an impact on the biological or ecological resource aspect, the economic aspect and the social aspect of any system [2]. Based on these three divisions, Elkington developed the triple bottom line (TBL) concept in 1998, which calls for corporations to consider and monitor their overall impact on the environment and society, as well as its financial gains, creating a "bottom line" for each [3]. In the same year, Robinson and Tinker developed this concept further by stating that an organization, or governing body, can only make manufacturing decisions with no compromise across the economy, environment and society by integrating decisions [4].

Twelve years later, Hahn et al. argued that even through the mainstream of the literature theorize on achieving economic, environmental and societal growth simultaneously, the multi-faceted nature and complexity of the task implies that trade-offs and conflicts in corporate sustainability are still the rule rather than the exception [5]. This indicates that high level tools are required in order to simplify the complex, and aid decision-making ensuring no trade-offs to the three facets of sustainable development.

1.1 Sustainable Manufacturing

In modern times, sustainable manufacturing is of paramount importance to industry. As stated by Wyckoff "[sustainable manufacturing] is no longer just nice-to-have, but a business imperative" [6]. Increasing pressure towards sustainable development worldwide has been a driving force for companies to focus on balancing environmental protection, economic and social development. Following a series of corporate scandals including oil spills and sweatshop labor, organizations are expected to be more accountable and transparent. In other words they are expected to conform to corporate social responsibility [7].

1.2 Integrated Product Development

Integrated Product Development (IPD) is an idealized model for concurrent product development which integrates the three main disciplines of marketing, design and production. As discussed by Hein and Andreason, the main aim of the IPD approach is to have a successful business, therefore satisfying the customer's requirements [8].

1.3 Manufacturing Simulation

Modelling and simulation technologies hold tremendous promise for reducing costs, improving productivity and quality, and shortening the time-to-market of manufactured goods. Kibira and McLean state that manufacturing simulation is mostly used to provide support tools to facilitate manufacturing decision-making. Typically simulation studies will involve the modelling of particular aspects of current operations and the testing of scenarios, to predict the impacts of the proposed changes to the operations [9]. McLean and Leong discuss that simulation technology has become a top research priority that promises high gains. This is driven by the fact that manufacturing systems, processes and data are growing more and more complex, further increasing the need for high-level tools such as simulation [10].

1.4 Research Gap

Both Sustainable Manufacturing and Integrated Product Development have been identified as needs for an organization to increase competitiveness and agility in today's fast-changing industries. Both concepts indicate a certain level of complexity due to their multifaceted nature, requiring the use of elaborately designed tools and methodologies to obtain them, especially when combining the two. Refalo suggests that such a goal could be coined as Sustainable Integrated Product Development (SIPD) [11].

Developing further from Elkington's concept of TBL (Triple Bottom Line), SIPD's ultimate goal would be to consider a Quintuple Bottom Line (QBL), ensuring that manufacturing decisions would not compromise any of the five sectors, i.e. Product, Production, Business (which is linked with Economy), Environment and Society.

Digital factory simulation during decision making has shown vast improvements in efficiency and cost-effectiveness, as well as reducing time-to-market [12]. An opportunity is therefore identified in using Software Simulation as a tool for Sustainable Integrated Product Development, as well as presenting a number of challenges.

2 Methodology

In order to address this opportunity, a typical software simulation exercise was conducted with the aim of investigating how such a tool can be used for Sustainable Integrated Product Development decision-making. The concept was to generate a

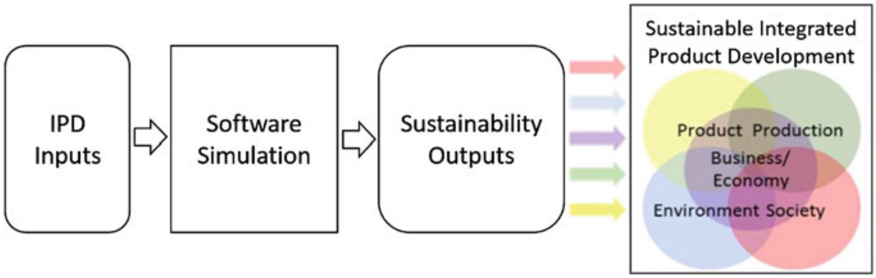

Fig. 1 Proposed methodology for using Simulation as a tool for SIPD

simulation model which answers IPD questions with outputs related to the three pillars of sustainable manufacturing (environment, economy, society), shown in Fig. 1.

A manufacturing line of a polymer product was chosen as a case study, and a simulation exercise was performed. Based on methodologies investigated from various literary works, with significant influence from Balci's methodology, the following framework was followed during the simulation case study.

The study started with efforts on understanding the system, followed by the identification of the simulation goals. To be able to explain the manufacturing line in detail, the real line was observed, and a value stream map was constructed as a conceptual representation of the current state of the manufacturing line. Next, a virtual model was constructed based on the conceptual representation using the software Tecnomatix Plant Simulation by Siemens, a software package designed specifically for the modelling, simulation and optimization of manufacturing, as well as process planning [13]. It is an ideal tool for the manufacturing line under study specifically due to its capability to model and simulate working shift systems, transportation systems, participants in the work and their assigned tasks, conditions such as working, pausing, waiting and so on.

The model outputs were designed to be in the form of sustainability Key Performance Indicators (KPIs), divided in three groups relating to environment, economy and society. Amrina and Yusof [14] suggest a comprehensive list of Sustainability KPIs, most of which could be suitable as simulation model outputs. However, not all the metrics were considered applicable for the study, and the list was reduced based on the applicability of historical data and available measurement methods at the manufacturing line under investigation. Whilst many more metrics could be used as simulation outputs, there would have been no means to validate and verify the output values, given the limitation in measuring such metrics at the real manufacturing line. A specific difficulty was encountered when attempting to select typical societal metrics such as job satisfaction and employee talent development.

In an attempt to include societal metrics, specifically related to Health and Safety, the distance walked by employees was measured throughout the duration of the simulation run. Whilst not providing much insight on the societal impacts of the manufacturing process, the distance walked by the operator may be directly linked to the fatigue experienced by the worker, or alternatively may contribute to a level of fitness resulting from the activity. Therefore the metric was chosen to at least shed light on the usability of software simulation for evaluating the impact a manufacturing decision would have on the employees.

The model was validated by analyzing its performance and its outputs, and comparing it to the real life manufacturing line, using the methodologies described by Sargent [15]. Table 1 compares the values on the simulation scorecard with actual values from the plant, showing a maximum variation of 8.42 %.

Law and Kelton discuss that a variation of 10 % is a widely accepted value during simulation modelling, making the developed model satisfactory for the case study [16]. The actual data from the plant was obtained from various sources including historical data, budgeted costings for labor, and cost of materials, consumption of subassemblies and raw materials, as well as direct measurements from the manufacturing line.

Having obtained a model representative of the real system, different scenarios were designed and run by changing the inputs. The scenarios included specific changes in product, production and business aspects, in order to ask IPD questions to the model. After running the scenarios, the results obtained were analyzed and documented, getting insight on the impact resulting from said scenarios [17–20].

Table 1 Validation Run Scorecard comparison with actual data

		Model	Actuals	Variation
Environmental performance				
1. Resource util.	(1) Energy utilization per unit	0.04444 kWh	0.0485 kWh	−8.42°%
2. Waste	(2) Solid waste generated per unit	4.534 g	4.701 g	−3.56°%
Economic performance				
3. Quality	(3) Scrap cost per unit	0.0315 €	0.0313 €	0.47 %
	(4) Reject rate	15.72 %	16.23 %	−3.13 %
4. Cost	(5) Overhead cost per unit	0.05071 €	0.0541 €	−6.33
	(6) Inventory cost per unit	10928 €	N/A	N/A
	(7) Unit cost	0.53854 €	0.5533 €	−2.66 %
	(8) Labour cost per unit	0.04538 €	0.0483 €	−6.08 %
5. Delivery	(9) Overall cycle time	4.33735 s	4.618 s	−6.08 %
Social performance				
6. Employee	(10) Daily kms walked per worker	1.994 km	N/A	N/A

3 Results

3.1 Scenario 1—Improving Machine Quality

In the first scenario, the quality performance of one of the machines was altered by changing the scrap rates of the machine. The current scrap rate of the case study which was studied is at 5 %. A series of scrap rates between 1 and 9 % were applied and the percentage variations obtained for each run are shown in Table 2.

Most significantly, there was a marked impact in environmental sustainability, as improving the quality of a machine results in a reduction in energy consumption and a reduction in solid waste. In terms of economical sustainability, there is an immediate benefit with a reduction in scrap costs, as well as creating a more profitable product overall. A slight negative impact is detected by the model in societal sustainability, due to the increased walking distance as manufacturing outputs increases with less scrap. Metrics for job satisfaction, employee morale, as well as corporate social responsibility would most probably improve with reduced scrap, but this is not visible from the model.

This scenario has shown, that by changing factors from the production and by extension, the production design, the simulation provided predictive results on the impact that this change would have across the Triple Bottom Line, and not only on environmental performance.

Table 2 Variations in scorecards for simulations with altered machine quality performance

	1 % scrap	3 % scrap	5 % scrap	7 % scrap	9 % scrap
Environmental performance					
(1) Energy utilization	−3.36 %	−1.72 %	N/A	1.72 %	4.18 %
(2) Solid waste	−40.57 %	−20.30 %	N/A	20.12 %	40.40 %
Economic performance					
(3) Scrap cost	−54.96 %	−27.51 %	N/A	27.32 %	54.79 %
(4) Reject rate	−21.88 %	−10.92 %	N/A	10.71 %	22.15 %
(5) Overhead cost	−3.47 %	−1.77 %	N/A	1.83 %	4.38 %
(6) Inventory cost	0.14 %	0.17 %	N/A	−0.12 %	−0.53 %
(7) Unit cost	−5.86 %	−2.84 %	N/A	3.39 %	6.74 %
(8) Labour cost	−3.49 %	−1.78 %	N/A	1.84 %	4.40 %
(9) Cycle time	−3.49 %	−1.78 %	N/A	1.84 %	4.40 %
Social performance					
(10) Daily kms walked	0.80 %	0.33 %	N/A	−0.40 %	−1.09 %

3.2 Scenario 2—Changing the Shift Pattern of the Loading/Packaging Personnel

In the second simulated experiment, the shift pattern of the packaging personnel was changed from a two-shift basis to a three-shift basis. This would imply an increment in wages, but the same labor hours dedicated to the process since the packaging process is not the bottleneck of the manufacturing. This was done in order to eliminate the buffers accumulating during the inactive night shifts. The scorecard obtained is shown in Table 3, with variation to the scorecard obtained in the Validation Run.

This scenario presents small changes in the economic pillar of sustainability by reducing Inventory Costs which was actually the target of this scenario, whilst increasing Labor Costs and Overhead Costs. Space is many times a commodity in a manufacturing environment, so dropping buffer sizes could justify the increased costs. Implementing such a change would only require shop floor employees to change their shift patterns, meaning that it would have no significant impact on the business aside from the increased labor cost. On the other hand, the simulation run presents no insight on the impact that the change would have on the employees, even though it implies a change in their lifestyles. This example gives an indication of the limitations of the simulation model obtained, as well as the difficulty in simulating societal considerations.

3.3 Scenario 3—Changing Stack Size of Bins

In the manufacturing line under study, material is transferred from one process to the next in bins, typically stacked in groups of six. For the third scenario, the stack

Table 3 Scorecard for Revised Shift Pattern with variation to Validation Run

			Variation
Environmental performance			
1. Resource utilization	(1) Energy utilization per unit	0.04443 kWh	−0.02 %
2. Waste	(2) Solid waste generated per unit	4.53562 g	0.04 %
Economic performance			
3. Quality	(3) Scrap cost per unit	0.0315 €	−0.01 %
	(4) Reject rate	15.77 %	0.32 %
4. Cost	(5) Overhead cost	0.05232 €	3.17 %
	(6) Inventory cost	10423.35 €	−4.62 %
	(7) Unit cost	0.54014 €	0.30 %
	(8) Labour cost	0.04699 €	3.54 %
5. Delivery	(9) Cycle time	4.33735 s	0.00 %
Social performance			
6. Employee	(10) Daily kms walked	2.002 km	0.36 %

Table 4 Scorecard for Reduced Stack Size with variation to Validation Run

			Variation
Environmental performance			
1. Resource utilization	(1) Energy utilization per unit	0.04443 kWh	−0.03 %
2. Waste	(2) Solid waste generated per unit	4.54412 g	0.22 %
Economic performance			
3. Quality	(3) Scrap cost per unit	0.0315 €	0.22 %
	(4) Reject rate	15.75 %	0.18 %
4. Cost	(5) Overhead cost	0.050S0 €	0.13 %
	(6) Inventory cost	8671.03 €	−20.55 %
	(7) Unit cost	0.53S70 €	0.03 %
	(S) Labour cost	0.04547 €	0.20 %
5. Delivery	(9) Cycle time	4.34508 s	0.20 %
Social performance			
6. Employee	(10) Daily kms walked	2.223 km	11.45 %

size of materials was changed from six to five bins, implying a material transfer yield decrease of 16.7 % (one-sixth). The scorecard for this run is shown in Table 4.

The scorecard achieved shows limited changes in the overall process performance but represents a great reduction in Inventory Cost, resulting from the reduced content of every stack. The only other significant change is an increase in the distance walked by the employees, resulting from increased movement of stacks due to the lower yield from each movement.

This analysis has revealed that a simple solution such as reducing the stack size actually signified a greater reduction in inventory cost than Scenario 2. Furthermore the labor cost of the product was not significantly altered, whilst in Scenario 2, there was a marked increase in labor costs due to the rearranged shift patterns.

The scenario implies a negative impact due to the increased fatigue experienced by the workers. However considering that such an improvement was obtained without altering the shift patterns, one could speculate that the impact on society is actually less significant, although this is not directly visible from the model outputs. The simulation does not provide enough insight on the societal impact and a deeper analysis would be required.

3.4 Scenario 4—Changing Product Characteristics

The fourth scenario proposed changing the dimensions of one of the components of the finished product, i.e. the tube length. The tube length is currently set at 145 mm and by changing its length, the functionality of the product is not altered. To test the effects of this change, several simulations were run with different tube lengths, the results of which are shown in Table 5.

Table 5 Scorecard variations for altered tube lengths

	100 mm	125 mm	145 mm	175 mm	200 mm
Environmental performance					
(1) Energy utilization	0.00 %	0.00 %	N/A	0.00 %	0.00 %
(2) Solid waste	−7.88 %	−3.50 %	N/A	5.25 %	9.63 %
Economic performance					
(3) Scrap cost	−2.03°%	−0.94 %	N/A	1.23 %	2.32 %
(4) Reject rate	0.00°%	0.00 %	N/A	0.00 %	0.00 %
(5) Overhead cost	0.00 %	0.00 %	N/A	0.00 %	0.00 %
(6) Inventory cost	−0.36 %	−0.06 %	N/A	0.39 %	1.46 %
(7) Unit cost	−2.35 %	−1.05 %	N/A	1.56 %	2.86 %
(8) Labour cost	0.00 %	0.00 %	N/A	0.00 %	0.00 %
(9) Cycle time	0.00 %	0.00 %	N/A	0.00 %	0.00 %
Social performance					
(10) Daily kms walked	−0.17 %	−0.06 %	N/A	0.23 %	0.53 %

Several changes across most metrics were observed. Reducing the tube length results in significant savings directly resulting from a reduced usage of raw materials, but also resulting in reductions in inventory costs and higher yields from raw material transfer, reducing employee fatigue as well.

This scenario is a perfect example of how an IPD question, with changes in product design, having an impact on the production as well as the business aspects, obtains sustainability metrics as outputs, across the economic, environmental and societal pillars. This can also be extended to include changes in other product details. However, many times these may result in the production process being altered.

3.5 Scenario 5—Reducing the Workforce

In the fifth scenario, the workforce was reduced from a total of thirteen workers down to ten, the results of which are shown in Table 6. The mechanism that made this possible was to instruct the machine operators to perform visual inspection tasks as well.

The scenario has shown extensive improvements in the economic pillar, as the lower Labor Cost has a direct impact on the profitability of the product. Whilst the model outputs indicate that the reduced head count did not alter the yield of the global process, this was only within the virtual time length of the simulation run. Observing the model directly during operation showed that the set-up would only allow for a few weeks of production with full yield until the buffer levels between machines deplete, at which point, production would slow down significantly due to a slower availability of product.

Table 6 Scorecard for reduced workforce

			Variation
Environmental performance			
1. Resource Utilization	(1) Energy utilization per unit	0.04442 kWh	−0.05 %
2. Waste	(2) Solid waste generated per unit	4.38667 g	−3.25 %
Economic performance			
3. Quality	(3) Scrap cost per unit	0.0308 €	−2.23 %
	(4) Reject rate	15.09 %	−4.02 %
4. Cost	(5) Overhead cost	0.03987 €	−21.39 %
	(6) Inventory cost	10234.78 €	−6.35 %
	(7) Unit cost	0.52699 €	−2.14 %
	(8) Labour cost	0.03454 €	−23.89 %
5. Delivery	(9) Cycle time	4.33735 s	0.00 %
Social performance			
6. Employee	(10) Daily kms walked	4.206 km	110.88 %

With regard to societal sustainability, the model only gave information about the increased fatigue experienced by the workers. Other implications may be possible. The societal impact of reducing the workforce could be immeasurable as motivation dips lower, whilst also reducing the employability of the process. This is all valuable insight on the sustainability of the process which could be used when considering the business and the production aspects. A more advanced simulation model, with better focus on societal metrics could provide even more guidance with regard to societal sustainability, which is currently not visible with this simulation study.

4 Conclusions

A simulation model which allows for the testing of different scenarios, relevant to the case study itself, was achieved. By asking IPD questions, the model gives predictive outputs related to the pillars of sustainability, therefore aiding decision-making with consideration towards the five components of Sustainable Integrated Product Development. This study has shown that simulation modelling with Tecnomatix can provide valuable insight on the behaviour of systems when subjected to changes, and can therefore be used as a tool to answer questions related to SIPD.

Whilst showing that simulation is a valuable tool for Sustainable Integrated Product Development, this study is not exhaustive in the use of applicable metrics, indicating that the above exercise can be extended to other metrics, specifically in the use of environmental metrics. Environmental implications and considerations can easily be added to the virtual model in the form of attribute data. The same cannot be said for societal considerations. With the current tools, software simulation is still rather inadequate for measuring the societal sustainability of a manufacturing line, and therefore requires more development for its effectiveness in achieving a tool for Sustainable Integrated Product Development with a complete Quintuple Bottom Line focus.

The exercise provided predictive information on the changes in behaviour a system would undergo when subjected to different inputs. The changes across the different metrics may have opposing consequences. This indicates that different metrics may require different weightings in order to choose between proposed changes. Investigation about the methodology for weighting different metrics would be of further value to the use of simulation for SIPD decision-making.

Throughout the duration of this study, limitations were encountered. These include insufficient data regarding societal factors specific to the plant and difficulty in measuring certain parameters and metrics. A more thorough investigation to deal with these issues could provide further insight and knowledge towards a better use of software simulation for sustainable integrated product development.

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