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Development of a multi-product cost and value stream modelling methodology

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In support of the life-cycle engineering of manufacturing enterprises (MEs), there is a need to provide reusable computational representations of organisational structures, processes, information, resources, and related cost and value flows. Current best process mapping techniques do not suitably capture key time-based attributes of ME systems, particularly with respect to the dynamics associated with multi-product work flows through shared resource systems. However, multiple work-flow dynamics will likely impact significantly on cost and value generation, and if this kind of dynamics cannot be effectively modelled, the use of process mapping will be limited as a basis for decision-making. Therefore, this paper presents an integrated multi-product dynamic cost and value stream modelling methodology with the embedded capability of capturing aspects of dynamics associated with multiple product realisations in MEs. The first part of the research presented in this paper shows the application of an enhanced and integrated use of process mapping and enterprise modelling techniques in a case study involving a POP manufacturing company in the UK. When compared with the use of current lean-based value-stream-mapping techniques, case study results obtained when using the first part of the modelling method have led to improved solutions to problems of: analysing and estimating cost and values; and improving the design and operation of multi-product realising systems.

Keywords: manufacturing enterprise (ME); value stream mapping (VSM); computer integrated manufacturing open system architecture (CIMOSA); enterprise modelling (EM)

1. Introduction

Many researchers have indicated that today’s MEs are in permanent change, and therefore it behoves any ME to adopt strategies and suitable solution technologies that allow them to become flexible and responsive to change (Bernus and Nemes 1996, Weston 1999, Sterman 2000, Hitchins 2003, Weston et al. 2009). To achieve this, a carefully matched philosophy, enabling strategy and solution technology, is required (Weston et al. 2009; Figure 1). This requires ongoing control and management of manufacturing processes with a view to deploy dynamic modelling techniques to enable smart decisions based on scientific verification (Gunasekaran and Kobu 2002, Vernadat 2002).

Process engineering tools, especially of the value-stream-mapping type, have been instrumental in the implementation of lean (Hines and Nick 1997, Bicheno 2000, Womack and Jones 2003, Lian and Van Landeghem 2007). Typically, value stream mapping has been reported to be a useful tool in transforming mass production systems to lean production systems (Liker 1998). Further claims include the delivery of products in time; at a lower cost, of high quality, and on a continuous basis (Lee 2005). In principle, value stream analysis can help specify processes with: integrated single piece flow; defect prevention; production pull; continuous waste reduction; flexible team-based work and active involvement and close integration with suppliers (Bicheno 2000). In practice, value stream maps are known to help identify (and therefore help eliminate or at least reduce) the wasteful activities that customers would not wish to pay for, hence making it a useful tool for process improvement (Boeing 2000).
It follows that value stream mapping has proven effective in many manufacturing organisations. Pavnaskar et al. (2003) argue that:

- In the use of VSM, the analysis of the initial situation is based on the acquisition and treatment of numerical data, and uses a graphical interface that makes it easier to see the relationship between material and information flows.
- The systemic vision provided for each product family reflects manufacturing system inefficiencies. This is also highlighted by Jones and Womack (2003).
- A common language can be provided for the team to unify lean concepts and techniques in a single body. This is also highlighted by Baker (2003).
- There is the possibility of VSM being the starting point of strategic plan improvement (Gregory 2003).

One clear issue about VSM worth investigating is the possibility of it being a useful tool for manufacturing systems redesign, especially, in a complex multi-product environment. A number of researchers have provided an insight on this aspect of manufacturing process engineering. They have reported that some of the limitations of VSM include the following:

- Because most VSMs are ‘paper-and-pencil-based’, the accuracy level is limited, and the number of versions that can be handled is low (Braglia et al. 2006, Lian and Van Landeghem 2007).
- In complex manufacturing environments with multi-product flows, it is extremely difficult to map all the process routes (Duggan 2003, Braglia et al. 2006, Agyapong-Kodua et al. 2009).
- It is also not suitable for dynamic analysis (McDonald et al. 2002, Agyapong-Kodua et al. 2009).

Based on a review of existing literature on methodologies and tools for the redesign of manufacturing systems, Serrano et al. (2008), after evaluating the performance of VSM in manufacturing systems design, indicated that in broad terms, ‘flow diagram charts’, ‘structured systems’, ‘architectural systems’, ‘modelling and simulation software’ are the four main tools currently deployed for manufacturing systems redesign and engineering. They noted that each of these tools is used in isolation. Further they observe that although software has been developed to support
VSM applications, in general the use of this software is closely coupled to VSM framework concepts, which could be a limiting factor in respect of the life-cycle engineering of ME systems; whereas if a focus on VSM concepts alone is appropriate, time involved in acquiring the required software and providing training can also be limiting (Baines et al. 1998, Oyarbide 2003, Aguilar-Savén 2004, Serrano et al. 2008).

The methodology proposed in this paper is divided into two phases. The first part involves the creation of an enhanced static cost and value stream model via an integrated use of enterprise modelling, cost-engineering techniques, and strengths of process mapping tools. The output of this first phase can usefully support a number of forms of business analyses. The applicability of the first part of the methodology was tested through a case study in a POP manufacturing company based in the UK. The second part, which is not reported here, involved the use of discrete and continuous simulation modelling techniques to test ‘what if’ scenarios that formed the basis for the derivation of ‘to-be’ models. The second part of the case study work is reported in the first author’s PhD thesis (Agyapong-Kodua 2009). Subsequent sections of this paper specify the multiproduct flow dynamic cost and value stream modelling methodology.

2. Requirements for multi-product flow and dynamic value and cost streams in MEs

An extensive review of techniques related to current manufacturing philosophies and their associated technologies has been provided by one of the authors (Agyapong-Kodua 2009). In this earlier work, tools with potential to define, measure, and utilise aspects of value and cost information in manufacturing processes were classified as:

- process mapping (PM) tools;
- enterprise modelling (EM) tools;
- system dynamics (SD) modelling tools; and
- business process simulation modelling (SM) tools.

The tools reviewed included, among others, 14 PM tools (e.g. overall lead time map (Hines and Nick 1997, Bicheno 2000), process activity map (Hines and Nick 1997, Bicheno 2000), product variety funnel (Bicheno 2000, Hines and Taylor 2000), push–pull map (Bicheno 2000, Hines and Taylor 2000), value stream map (Womack et al. 1990, Hines and Taylor 2000, Duggan 2003, Womack and Jones 2003, Lee 2005), etc.); seven EM tools: PERA (Williams 2002), ARIS (Scheer 1992), CIMOSA (AMICE 1993, Vernadat 1996), TOGAF (Marley 2003, Camarinha-Matos and Afsarmanesh 2008), IEM (Bermus et al. 2006), IDEFx (Roboam 1993), BPMN (White 2006); six SD tools: Causal Loops (Forrester 1961, Sterman 2000, Burns 2001, Burns and Ulgen 2002), Stock and Flows (Randers 1980, Sterman 2000, Binder et al. 2004), Petri Net (Peterson 1981, Zhou and Venkatesh 1999), Bayesian networks (Pearl 2000), Fuzzy logic (Batur et al. 1991) (Wang 1992), Neural networks (Minsky and Papert 1969, Gardner and Derrida 1988, Spooner et al. 2002); and seven SM tools: Lean Modeller (Visual8Co. 2006), Simul8 (Shalliker et al. 2005), iThink/Stella (ISEE 2007), Lean Enterprise (Visual8Co. 2006), Arena (Rockwell 2000), Witness (Lanner 2008), and Quest (Quest 2008). It was observed that many researchers have continuously attempted to introduce and improve existing process improvement tools to cater for the current needs of MEs. Unfortunately, the tools developed are uniquely strong only in their respective domains of business process engineering, enterprise integration, systems thinking, and value and cost engineering. Observing the strengths of these tools, it was noted that to effectively model multi-product cost and value streams for decision-making in a dynamic manufacturing environment, the following modelling attributes will be required:

- ability to analyse multi-product flows (particularly through shared resource systems) and their associated product dynamics;
- the possibility to identify and capture aspects of complexities and dynamics in MEs;
- the suitability of the mapping tool to assist in complex manufacturing systems and process redesigns;
- the ability to reflect causal impacts of activities in MEs especially in financial terms;
- the possibility to measure process cost without distortion;
- the ability to quantify value addition through a given process;
- availability of suitable constructs for value and cost modelling;
- the ability of the tool to support business analysis, especially in a virtual environment;
- the capability to decompose processes into elemental activities to enhance understanding and process analysis;
- the suitability of the tool to support CIM and IT principles.
3. Gaps in existing cost and value stream modelling techniques

In the review reported in Agyapong-Kodua (2009), it was observed that in relation to the requirements for modelling multi-product dynamic value and cost streams in MEs:

(1) The PM tools were not very suitable for multi-product flow analysis. At best, enhanced versions of the VSM technique recognise the need for product classification to simplify or annex the effect of some of the challenges associated with multi-product flow dynamics.

(2) Also observed from the strengths and weaknesses of the mapping tools was that none of the tools was really good for capturing complexities and dynamics in MEs. This is because most of the tools were designed for mapping linear processes and do not reflect real-time dynamic instances of MEs. In terms of the reflection of cost and values realised by processes in MEs, process-based tools such as VSM, cost–time profile, and value-adding time profile can be enhanced to support activity-based costing.

(3) Analysing the various mapping tools, it was observed that none of the tools had formalisms which supported a detailed decomposition of processes. Decomposition of processes enables enterprise systems to be grouped into elementary bits for easier management. Also, there are no clear methodologies for defining processes and their associated activities. Because of the limited formalisms, enterprise knowledge cannot be fully capitalised, and the associated benefits of enterprise integration as a requirement in CIM cannot be enabled. Thus, on a more critical note, the process mapping tools do not render adequate support for the design and implementation of CIM systems. The idea of open systems architecture and standardised CIM modules which support the ‘plug and play’ approach is not harnessed in most of the methodologies.

(4) Literature has shown that value stream mapping has proven effective in many manufacturing organisations engaged in single product flow manufacture, and concepts of value streams have successfully been used in organisations deploying lean manufacturing techniques. However, value stream mapping was observed not to be an effective process redesign and improvement tool for manufacturing systems that need to realise multi-product flows. Apparently, the current best-practice approach to value steam mapping is not capable of mapping complexities and dynamics inherent in MEs. Also, existing literature on the lean approach to value stream mapping does not clearly show how values are quantified along process segments. The closest idea towards quantification of values is based on cycle and lead times. None of the other mapping tools could be used complementarily with the value stream mapping tool to help overcome these limitations.

Reviewing the strengths and weaknesses of EM tools, the authors observed that in general terms:

(1) The Enterprise Modelling (EM) tools, relative to process mapping tools, offered additional modelling concepts that enable the capture of semantically enriched models of various aspects of enterprises. Because of their unified approach towards CIM systems, they provide a uniform representation of enterprises that cause users to understand their operations in depth. In theory, enterprise modelling approaches facilitate the design and development of better processes and systems, and can improve the timeliness and cost-effectiveness of change projects in MEs, but full and industry-wide benefit in practice is yet to be realised.

(2) In analysing the possibility of using EM tools to depict multi-product flows in MEs, it was noted that most of the EM tools were process-based, and they generated models from the understanding of generic processes in companies. Additional work is therefore required to configure business processes around product classes.

(3) In meeting the requirements of CIM implementation and the fulfilment of international regulations such as ENV40003, the CIMOSA modelling methodology was observed to be one of the most complete and able to handle time, exceptions, and non-determinisms in model generation. There also exists the potential to combine best-in-class aspects of the value-stream-mapping technique in terms of product classification, cycle, and lead-time determinations, definition of waste and value, etc., to best-in-class model generation capabilities of the CIMOSA technique to support enhanced modelling of values in multi-product manufacturing environments. However, generally, EM tools are limited in their provision of adequate constructs for capturing essential dynamic attributes in enterprises.

In reviewing the capabilities of SD tools and techniques with the view to observe how an integrated VSM-CIMOSA technique can be supported to capture and model dynamic attributes, it was noted that:

(1) SD techniques offer a unique approach towards the modelling of complexities and dynamics in systems. In essence, they are useful tools for capturing and analysing factors that impact on processes and their executing agents, but in reality, without a process model, it is difficult to make full use of SD models in manufacturing environments and, most importantly, in CIM design and application. This is because in CIM environments, an enterprise or process model is very important and arguably should be the baseline for enacting process improvements.

(2) The strong mathematical bases of these modelling techniques discourage many manufacturing experts from deploying them. This is particularly so in the case of BNs, FL, NNs, and PN technologies. The CL technique, however, does not involve any complex mathematical expressions, and it is good in illustrating, qualitatively, the cause and effects evident in a system. Also observed was that the CL modelling technique could be used together with process modelling techniques to capture and analyse the causal impact of activities on various business-performance indicators. This will lend support for complex manufacturing-systems design. Also, by using CLs, factors that influence value generation and cost can be captured and embedded on process-based models for effective economic analysis of manufacturing processes.

(3) None of the system dynamics tools on its own was observed to be capable of modelling multi-product flows in manufacturing environments. However, they are able to capture factors that influence or impact on ME processes owing to multi-product flow phenomena. This is because they are not process-modelling tools and can only provide support by providing an understanding about the complexities and dynamics along the process segments.

For simplicity and first-stage qualitative analysis, it was considered that CL proves to be the most suitable. However, CL models cannot be simulated in their natural state and need to be transformed into equivalent simulation models before an in-depth process and business analysis can be performed. Based on these additional needs, a further analysis and comparison of some of the commercially available simulation modelling tools were carried out. The choice of tool reviewed was limited because of the study and research constraints, but the seven tools (Lean Modeller, Simul8, iThink/Stella, Lean Enterprise, Arena, Witness, Quest) chosen as the subject of review cover different classes of simulators. Generally, it was observed that:

(1) The Lean Modeller software provided modelling constructs and measurable parameters similar to the constructs deployed when using the conventional value-stream-map technique. It is easier therefore to translate value stream maps into equivalent simulation models in Lean Modeller. A primary limitation however is the fact that Lean Modeller can handle only single flow process models. When complexities increase, it becomes difficult to mimic real-life situations in Lean Modeller. A later enhanced version of the software, Lean Modeller Enterprise, is capable of depicting some aspects of multi-product flow and complexities in MEs, but its capability is still limited to applications in lean enterprises. Its counterparts, Simul8, Witness, Arena, and Quest, offer more extensive approaches towards complex multi-product flow modelling. On the other hand, the iThink software is a continuous event simulation tool and does not segregate products flowing in the enterprise. iThink is able to generate graphs, and based on the mathematical formulae underlining the model, different aspects of complexities can be captured and used to define possible effects on the enterprise. iThink is not a process-modelling tool and therefore lacks formalisms for detailed modelling of process logics and controls.

(2) On the other hand, to measure cumulative cost and values associated with complex systems, iThink provides a better approach than the discrete event simulation (DES) tools. This is because of the flexibility iThink software provides in defining mathematical relationships between process parameters. Once mathematical expressions are derived, iThink is able to generate futuristic values based on the intended use of the model. The limitation in this approach is that the cumulative results continuous event simulation provides are not helpful in achieving product differentiations that could support decisions on products which add more value to the ME or cost less to produce. Simul8, however, is able to differentiate product types and their associated cost implications on production systems.

(3) Causal effects which are shown by causal loop models can best be illustrated and quantified by the iThink modelling technique. In effect, causal relationships can best be described in iThink than in the discrete event simulation tools, but because iThink is not a process modelling tool it is difficult to match these causal
impacts on processes. Although the discrete event simulators can be used to provide more precise models, iThink requires less effort, and it is good at depicting overall business behaviour.

It is therefore envisaged that different continuous and discrete event simulation modelling tools of relative strengths could be used coherently to model aspects of processes such as queues, product flows, process routes, causal effects, stochastic events, resource utilisation, process times, material and information flows, breakdowns, etc., depending on the intended use of the models. When a simulation model of a process is created, it will be difficult to interpret fully. This is especially so until it is presented in the context of the overall enterprise model. However, attempts to present simulation models in the context of the broad enterprise may render it complex and inappropriate to support decision-making. Therefore, EMs will be required (1) to provide the needed backbone of modelling concept for SMs and (2) to explicitly describe the key properties context on which any simulated process segment needs to operate.

The above discussions and analyses have shown that VSM has been reported as one of the most effective mapping methodologies for designing and creating efficient manufacturing systems capable of adding value to inputs that flow through various aspects of manufacturing processes. A critical review has, however, exposed its practical limitations in the areas of multi-product flows, causal impacts and dynamics, cost realisation, decomposition formalisms, CIM systems design, and IT applications. It has also been observed that there are a number of EM, SD, and SM tools with complementary strengths to address the limitations observed in the VSM technique. The literature, however, has not identified these complementary modelling techniques for optimal modelling performance in industries. The author is of the view that the appropriate integration of the strength of these modelling tools and the establishment of verified transformation schemes from one stage of modelling to the other will provide an alternative modelling technique with greater capabilities for solving multi-product value streams and cost dynamics.

4. Derivation of multi-product flow dynamic cost and value stream modelling methodology

To help meet the requirement for multi-product dynamic cost and value stream modelling, a methodology consisting of the integrated use of enhanced aspects of various modelling techniques was proposed. The methodology comprises the uniform application of knowledge and techniques from enterprise modelling, process mapping, system dynamics, and simulation modelling. Through this integration, the weaknesses of each of the individual techniques are marginalised.

Figure 2 shows the various process stages involved in the proposed modelling method. At each process stage, the required inputs are described. For example, to generate enterprise models of MEs, key ME information will

![Figure 2. Proposed modelling methodology.](image-url)
be required. This can be derived by interviewing key knowledge holders in the ME and complementary use of ME data sheets. A number of public-domain EM architectures, methodologies, and techniques have been conceived to facilitate key aspects of process-oriented organisational design and change. Through the review, the CIMOSA modelling approach was observed to offer extensive sets of modelling constructs and well-studied decomposition formalisms for modelling enterprises at multiple levels of granularity. Using CIMOSA modelling, networks of processes are generated such that connections between process elements can be explicitly described and graphically represented. This is an essential way to help analyse the causal impact of activities on each other. Because of the detailed decomposition attributes made available with the CIMOSA technique, this means that operational activities can be captured in detail and modelled at suitable levels of abstraction, such that value addition and cost generation can be estimated at an acceptable degree of accuracy. The models generated can be used to analyse bottlenecks and other process-improvement factors that are within the scope of the mapping tools. Based on the authors’ experience in the use of CIMOSA modelling technique, the CIMOSA technique was considered useful for capturing enterprise knowledge; and related structured and unstructured information. Hence, the outcome of the first step (namely enterprise description) is a set of enterprise models describing in a specific business context the various processes and flows that exist in an ME. When using the modelling methodology introduced by this paper, the outcome of the CIMOSA Enterprise Model is transferred to the next stage of the modelling exercise together with other data on product types and operation times to generate what in this paper is termed a product-based ‘business process-oriented configuration’ (POC). The derived POC is supported with value and cost constructs together with various process parameters to form an enhanced static cost and value stream model capable of being used for various forms of static cost and value stream analysis. The end result of this first stage of ‘static modelling’ can be readily translated into ‘fit for purpose’ simulation models that can underpin various forms of dynamic cost and value stream analysis. The finally derived model is useful for multi-product flow dynamic analysis, causal impact demonstrations, dynamic cost, and value analysis, as well as providing a tool and specific case models for process improvement and process redesign.

Figure 3 further describes how various modelling capabilities of existing modelling techniques are integrated to form a comprehensive multiproduct dynamic cost and value stream model. As shown in Figure 2, enterprise models are generated through the application of the CIMOSA modelling technique. Process classification and other lean-based value metrics are derived through an existing VSM technique. The integration of enterprise models and process classification at stage 1 of the modelling process generates a product-based POC that is then combined with
the derived cost and value estimation metrics at stage 2. The outcome of this combination is a static cost and value stream model. At the next stage of modelling, the static model is transformed into DES and SD models depending on the modelling intent. The integration of the modelling techniques is based on files, transfer of data from one stage to the other, and the merging of constructs.

4.1 Detailed description of modelling stages

To apply the modelling methodology described in this paper, the steps below are required. These steps are based on the process flows shown in Figures 2 and 3:

1. Develop an enterprise model that helps decompose all relevant processes into their elementary processes or activities and their resources. Full details on creating this type of enterprise model can be obtained from Chatha and Weston (2005), Rahimifard and Weston (2007), and Agyapong-Kodua et al. (2009).
2. Generate a product family matrix by routing products through the enterprise process models. This will help derive a first-stage product classification (product-based POC).
3. Refine the initially derived product families based on the work content of processes.
4. Assign cost, value, and process information, and derive the static cost and value stream model.
5. Conduct static cost and value stream analysis.
6. Extend relevant portions of the static model into dynamic cost and value stream model.
7. Conduct dynamic cost and value stream experiments and analysis.

The authors are of the view that following the steps systematically can help generate a useful multi-product dynamic cost and value stream model. Details of how to realise these steps are provided in the subsequent sections.

4.1.1 Process decomposition

The proposed methodology starts off with the quest to comprehensively understand processes, associated flows, and resources that transform inputs into ‘useful units’ that meet the goals of the company under consideration. This naturally leads to the generation of a ‘big picture’ that informs the modeller and user about functional requirements in the organisation. In deriving the big picture, care is taken to underline the internal and external stakeholders of the ME, and special emphasis in terms of further decomposition is realised by detailing the requirements that are relevant to the current study. From the literature survey, it was observed that CIMOSA modelling templates provided suitable decomposition formalisms to help achieve this objective. In principle, the decomposition of processes in the manner described above will help capture almost all (if not all) processes within domains of interest and also promote an understanding of these processes, thus enabling the management of processes of interest. Because of the explicit description of interactions that exist in processes, when changes are made to process segments, their resultant effects on other processes can be readily understood and analysed, and, if necessary, modified.

4.1.2 Product classification

The literature has shown existing methods for classifying processes based on product routes, but the contribution made by the authors involves routing material through networks of CIMOSA-based business processes, POC, for the product under consideration. In terms of the process-based classification method proposed, different products realised by the ME are routed through an identified list of BPs placing particular emphasis on material flow routes. This is because the operating idea of value stream modelling in this paper is based on the fact that value is added to materials (including information and knowledge) to convert them in a way such that customers are willing to pay. The products that share similar process routes are grouped together to form one product family. A product family matrix is generated by forming a grid that contains a list of processes in the columns and a list of products in the rows. Matching the different products to their BPs will explicitly represent the end-to-end processes required to produce the various products. In complex organisations that realise multiproduct flows, this can be a tedious exercise, but the objective still remains in that products will need to be classified based on the similarities in their POCs.

Grouping products based on similarity of process routes is a useful initial way to classify products. The authors are of the view that further refinements will be required so that in approximate terms, products with similar
processing costs can be grouped. This is achieved by refining the product families based on process operation times. To limit product variety, ‘work content’ for each operation as defined by Duggan (2003) to be the total time required for one operator to perform all the needed operations from start to end is estimated for the different products. A work content range defined as the percentage difference between the highest work content and lowest work content is used to distinguish between ‘high and low work content products’ within the same family. This observation leads to a breaking down of the initial developed product families into subproduct families distinguishing between high and low work content products.

4.1.3 Derivation of static cost and value streams

In response to the need to improve upon the capabilities of existing value-stream-mapping techniques (in support of value and cost modelling, such that process cost distortion is minimised, and values can be quantified along process segments), the VSM method was reviewed critically and additional modelling constructs proposed. In the proposed method, resources are further classified into human beings, machines, IT (software and technology) and materials. During the initial modelling stages, the approach is designed to focus on BP levels, but because a collection of activity diagrams are explicitly linked during CIMOSA decomposition to respective BPs, detailed analysis can naturally follow. Thus, for every work station, cycle times, resource types and number, information, up time or efficiency, shift pattern, and process cost are noted. Additional data in terms of related monetary values are assigned to individual processes. The cost of realising respective BPs can then be generated by estimating the total cost of executing the set of activities that make up the BP. A further static analysis can be performed on the developed VSM. Key process improvements parameters, such as production lead times, waiting or queuing times, queue size, process cost, and throughput, can be used as the basis for deriving future state value stream models. Another perceived advantage is that by adopting this approach, value and cost generated at every process stage can be demonstrated as a ‘flow’. In reality, this is achieved through the combination of the strength of the conventional value stream technique and the CIMOSA decomposition capabilities. Because of the likely complications in demonstrating this approach for long and large value chains, decomposition and product flow are maintained at the BP level and decomposed to activity levels only when further analysis is needed. In real-life situations, hyperlinks can be readily developed for easy access to subprocesses.

4.1.4 Derivation of virtual simulation cost and value stream models

The derived static value and cost stream models can be used as the basis for a number of static qualitative analyses. Various estimates on the total cost consumed when running the process can be derived. Another possibility is to compare the values generated through running respective processes with the selling price of components or materials and deciding on options whether to buy or make. However, all these estimates are limited to the current state, and it will be difficult to predict likely occurrences and hence design or organise the manufacturing systems to meet unpredicted challenges. It is therefore deemed necessary to transform the static value stream models into dynamic value streams models. This is to satisfy the requirement for alternative business analysis in a virtual environment and also to support human systems, IT system, and CIM system developments. An extension of the static cost and value stream models into equivalent dynamic models also has potential to quantify benefits that can be derived from making manageable ME changes to process structures, products and material flows, resource assignments, and the like. Additional information such as actual processing times, resource and task allocation, product or process routings, machine-sharing mechanisms, setup times and history of machine failures can be incorporated into models when using some existing commercial simulation tools. Also, the adoption of any process improvement scheme such as push, pull, postponement, and the other solution technologies may require investments that will need to be justified before their implementation. Benefits from the adoption of any of these solution technologies can be verified through the deployment of virtual simulation models: specifying values and the associated process improvement indicators such as lead time, inventory, queue times, and cost. Most critically, many businesses are often concerned primarily with short-term profit margins, and hence virtual models of value and cost streams will be helpful in quantifying potential benefits of change in the long and short term. Another objective to be realised through the application of virtual simulation models is to observe potential improvements that can be derived through the segmented analysis of product types and their associated individual dynamics. Also, cost and values generated through the production of different products should be able to be analysed so that management decisions related to specific products can be realised. Alternative manufacturing scenarios can also be investigated before
their implementation. Discrete event simulation tools are suitable for such analyses. Thus, Simul8, a commercially available process simulator is proposed to be useful. The developed Simul8 model becomes the dynamic cost and value stream model for process improvements. The static cost and value stream model becomes the backbone for the enhanced dynamic cost and value stream model. Thus, various factors impacting on decisions related to future state value stream models can thus be investigated.

5. Case application of multiproduct dynamic cost and value stream modelling methodology

The POP manufacturing company was founded in 1968 purposely for small-scale moulded-plastic parts manufacturing. Currently, the company is specialised in the design and manufacture of quality, three-dimensional point of purchase (POP) and shop equipment. In line with the specified requirements in section 2 and the needs of POP Ltd, it was decided that the research outcomes would consist of the following:

(1) A comprehensive multi-product static cost and value stream model. This will demonstrate how analyses of multiple product flows can be achieved and hence used as the basis to manage product variability. By achieving this, business processes responsible for various product groups will be understood and analysed. Potentially, wastages in process executions and improvements will be identified. This method will be based on the use of an already-established modelling technique that consists of the unification of VSM and CIMOSA modelling formalisms. The significant difference relative to current best practice of mapping processes will be the ability to generate product-based POCs. A number of static analyses depicting the current state of the business will be conducted for the processes modelled. Most importantly, understanding of processes will be verified such that the static model becomes the backbone for further business process analysis in POP Ltd.

(2) A dynamic multi-product cost and value stream model with simulated applications. To enable the testing of alternative business ideas that might impact positively on the business profitability and competitiveness, the static value stream model will be enhanced into a virtual dynamic simulation model so that results can be visualised before their implementation. By adopting this approach, potential results of the impact of alternative manufacturing and planning policies such as pull, push, lean, agile, etc. on cost and value generation can be deduced and discussed so that best decisions are made before resources are committed to the decision. The dynamic multiproduct flow cost and value stream models will assist in identifying potential means of introducing ‘flow’ in the production system; reducing inventory and production lead times, minimising impacts of product complexities and variance, reducing cost, and improving values for better business process efficiencies.

5.1 Data collection at POP Ltd

To help derive multiproduct flow dynamic cost and value stream models of POP Ltd, the proposed modelling methodology as specified in Figure 2 was followed. Therefore, at the initial stages of the research, company data from primary sources were gathered. Based on the understanding derived from the data gathered and established CIMOSA modelling formalisms, a graphical model representing the ‘big picture of POP Ltd’ was determined. Initial data acquired from the change manager, who was the main actor from POP Ltd, were in the form of an organisational chart depicting the various departments and human resources deployed in the company. In addition, a factory layout was obtained from the change manager to help identify where the offices and production shops were located. To help understand how customer orders are received and converted to production orders, the decision was made to meet the sales manager for a formal interview and discussion. In stages, all the managers and supervisors of the concerned departments were interviewed. By interviewing these knowledge holders, a clear picture of how processes were realised was obtained. In addition, how processes interact with each other was identified. Exemplary products were selected and followed through the entire process network to understand the various flows and interactions that existed between processes. A textual description of all the processes studied was prepared and submitted to the change manager for verification and correction. After the verification of the report, the authors were of the view that knowledge about POP Ltd’s processes was fairly accurate, and hence an enterprise model externalising understandings and current state operations of the company could be created. While awaiting the response of the report from the Change Manager, further specific data related to cost and value estimations were requested from the sales department, production shops, and accounts department.
One of the data types requested was the product types produced over 3- to 6-month periods. These data were to help identify the seasonal variations in demand, as more than one period of data could usefully inform aspects of seasonal variation. These data were to help understand customer orders and values these orders give to the company. This was again to form the basis of classifying products and focusing on relevant product classes. When the need for this data was discussed with the change manager, he requested that the sales department helps generate a sales report specifying the different product types delivered to customers covering the period June 2007 to November 2007, inclusive.

To understand how these product types match up to the business processes of POP Ltd, it was considered necessary to have data describing the historic workflows through identified business processes involved in realising the different product types described by the sales data. It was initially difficult to determine how products were routed through the production processes, but it was realised that after ‘top-level’ production plans are prepared by the planning department, each production shop prepares job schedules that describe the type of products required to be produced in the shop. Thus, previous production schedules were reviewed and matched with the sales data already provided. This gave a formal description of the product–process relationships that were vital for the development of multiproduct flow value streams.

The next data requested were operation times, make spans, production lead times, product delivery dates, and resources involved in realising the products mentioned in the sales report. Some of this information was available on their old production plans except that the change manager confirmed that they were not very accurate. Thus, a decision was taken to perform time studies on a few of the product types described in the sales data. Delivery dates were obtained on the sales data, and production lead times were specified on the assembly capacity plan. After a careful examination of these data and the few time studies conducted, a discussion was held with the change manager and to help indicate in context, the operation times, make spans and lead times of some of the operations. Other accounting data such as overheads, production cost, prices of products, rates of pay, material cost, depreciation, etc. were requested from the accounting department, but for the sake of confidentiality, the figures used in this paper are not the exact accounting figures. The logic, ratios, and difference between accounting figures were maintained in order to give a precise representation of the company.

5.2 Development of enterprise model of POP Ltd

After the change manager verified the content of the initial report describing the authors’ understanding of the processes at POP Ltd, it was decided at the next stage of the research to create an enterprise model that best represents graphically, the ‘as-is’ processes and flows in POP Ltd. After reviewing the company organisation charts, production flow charts, and data gathered through interviewing relevant sectional managers in the company, a table was created to help specify the observed processes, their associated subprocesses as well as the objectives of the captured processes. This was necessary to help discussions on our perceived business, manufacturing, and engineering environments of POP Ltd. This was also to serve as the starting-point for the creation of the enterprise model for POP Ltd. A context diagram showing the nine enterprise domains (DMs) observed to be relevant to the ‘manage and realise POP products’ in POP Ltd is shown in Figure 4.

As explained in the authors’ previous publications (Ajaefobi 2004, Agyapong-Kodua et al. 2007, 2009), after creating context diagrams, enterprise domains are decomposed into their respective domain processes (DPs) and utilised in an interaction diagram to show the various flows and process interactions that exist between DPs. Figure 5 shows the top-level interaction diagram showing the process interactions that exist between the various DPs. The symbols used in the interaction diagram are standard CIMOSA constructs. Their meanings are provided in the title block shown in Figure 4. From the top-level interaction diagram, it can be seen that customer orders are received through the ‘provide orders’ domain process (DP1). These orders are released to the ‘front end’ domain process (DP3). In the front end domain process, customer orders are converted to design data and order specifications that are transferred to ‘produce and deliver’ (DP4) and ‘manage business’ (DP5) domain processes respectively. The design data so created consist of ‘planograms’, product designs, kit lists, tool designs, and graphic designs. The order specifications on the other hand refer to a list of documents including BOMs, delivery dates, and other product information. In the ‘manage business domain process’ (DP5), the order specifications are converted to production plans and ‘shop-floor travellers’ and purchase orders for materials and subparts. The production plans and shop travellers are routed back to the ‘produce and deliver products’ domain process (DP4). In response to the purchase orders sent from DP5 to the ‘supply raw material’ and ‘produce subcontracted parts’, raw materials, parts...
and finished subcontracted parts are delivered to DP4. After parts supplied are checked in DP4, DP5 makes payments to suppliers and subcontractors.

DP4 produces and assembles various products based on the design data received and delivers finished POP products to customers. The finished products are presented with delivery documents and manuals. While executing these processes, performance reports are prepared and delivered to the ‘provide support services domain process’ (DP8). DP8 arranges and replaces all necessary equipment, IT, and software as per the process requirements. In addition, current product information and process performance reports are monitored by the ‘process and product improvement domain process (DP9).

At the next stage of the enterprise modelling exercise for POP Ltd, three structure diagrams were created to describe the decomposition of DPs 3, 4, and 5. Decompositions of DPs 3, 4 and 5 resulted in 46 business processes (BPs). Further sub- and sub-subinteraction diagrams were created to depict the interactions that existed between the respective BPs described by the structure diagrams. For reasons of clarity and inadequate space, these diagrams are not shown here. After the BPs were identified, because the intended purpose of further decomposition is for cost and value stream analysis, a spreadsheet was designed to collect actual activities required to fulfil the identified BPs. In addition to identifying the stepwise activities, the template was used to capture the operational times of each activity, delays, resources required, information, and materials necessary to complete the BPs. This was done for each of the BPs. An example of an activity diagram representing the ‘as-is’ activities required to fulfil ‘make digital prints’ (BP4.1.1.4) is shown in Figure 6.

The enterprise model for POP Ltd enabled a thorough understanding of the processes involved in the production of parts at POP Ltd. This implied that with an appropriate chain of processes identified as being responsible for the realisation of particular products, configurations of business processes can be modelled for the different products. As a result of this need, products were matched with their respective processes and used as the basis for determining process-based-product types. The next section explains how this was achieved in POP Ltd.

Figure 4. Context diagram of POP Ltd.
5.3 Process-based product classification

To limit the impact of product complexities, at the first stage of the classification exercise, products that are routed through the same processes were classified into one group. This was achieved by creating a matrix of ‘value-adding BPs’ and matching them to the products. From the sales data for the period June 2007 to November 2007 (not shown), products were matched with their respective BPs. The change manager assisted in sorting out these sales data, since most of the products had been produced before the commencement of the research in POP Ltd. In all, a total of 3725 different products were analysed. By using the production records and also with support from the change manager, the products were classified into their production batches, product types, and their respective process routes. Tables 1 and 2 show the results of the first-stage process-based product classification. The classification was based on BPs related to DP3 and DP4. Although normally, in modelling multiproduct flow cost and value streams, process classifications are based on ‘direct value adding processes’, it was considered necessary in this case to include the front-end business processes of ‘obtain and process order’ (BP3.1), ‘create designs’ (BP3.2), and ‘develop prototypes’ (BP3.3). This was because these processes made a significant difference in how downward processes were designed and realised. ‘Despatch finished POPs’ (BP4.3) was not included in the list of processes for classification purposes, because obviously it was a common process for all products. During the first stage of the classification, it was observed that out of the 3725 products, components of 385 products went through all the identified business processes. This class of products, which required essentially all the business processes, was called ‘standard units’. The next type of products required all processes apart from some design and prototype processes, such as: create graphic designs (BP3.2.3), create product designs (BP 3.24), develop prototypes (BP3.3.1), and
inspect prototypes (3.3.2). This set of products was called ‘repeat units’. Because they were repeat orders, graphic and product designs already existed, and prototyping of parts was not required. The next set of products did not require ‘planograms’ or a new BOM creation. In addition, product and graphic designs were not required. Final product assembly processes were also not required. This class of product was termed ‘rerun or update kits’. The last group of products based on the similarity of processes was called ‘graphic only kits’. These were products that required mostly graphic design and printing processes. Details of products belonging to these product classes are not shown for the sake of size and confidentiality.

Data related to the process times for each of the products were further reviewed. The review showed that within the same product class, further classifications of products were necessary, considering total processing times. This was considered necessary to limit the complexities involved in grouping products of large processing time variations together. This is particularly so if the end goal of the classification exercise is also to test the possibility of implementing pull or lean in the production systems. Total work content criteria based on Duggan (2003) were used to reclassify the products into six subgroups. Table 3 shows a summary of the final derived product families.

A range for determining work contents of the same product family was estimated as:

$$\text{Range} = \frac{\text{highest} - \text{lowest}}{\text{highest}} \times 100. \quad (1)$$

All products classified as low standard units were within 30% of the average work content for that product family. Products classified as ‘high standard products’ were above 30% of the average work content of the ‘low standard units’.

Figure 6. Activity diagram for ‘make digital prints’ (BP4.1.1.4).
Table 1. Process based product classifications.

<table>
<thead>
<tr>
<th>Product groups (Stage 1)</th>
<th>Obtain and process order (BP3.1)</th>
<th>Generate designs (BP3.2)</th>
<th>Develop prototypes (BP3.3)</th>
<th>Design inspect (BP3.3.1)</th>
<th>Prototypes (BP3.3.1)</th>
<th>Make prints (BP4.1.1)</th>
<th>Make prints (BP4.1.1.1)</th>
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</thead>
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<tr>
<td>Standard units</td>
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<td>X</td>
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<td>X</td>
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<tr>
<td>Repeat units</td>
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<td>X</td>
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<tr>
<td>Rerun or update kits</td>
<td>X</td>
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<td>X</td>
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<tr>
<td>Graphic based kits</td>
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<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

DP4 produce and deliver

<table>
<thead>
<tr>
<th>Product groups (Stage 1)</th>
<th>Screen dev. (BP4.1.1.1)</th>
<th>Screen print-manual (BP4.1.1.2)</th>
<th>Auto Screen Printing (BP4.1.1.3)</th>
<th>Digital Printing (BP4.1.1.4)</th>
<th>Lam’ion (BP4.1.1.5)</th>
<th>Platen Printing (BP4.1.1.6)</th>
<th>Pad Printing (BP4.1.1.7)</th>
<th>Print (BP4.1.1.8)</th>
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</thead>
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<tr>
<td>Standard units</td>
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<td>X</td>
<td>X</td>
<td>X</td>
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<td>Repeat units</td>
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<tr>
<td>Rerun or update kits</td>
<td>X</td>
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<tr>
<td>Graphic based kits</td>
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</tr>
</tbody>
</table>
### Table 2. Process based product classifications.

<table>
<thead>
<tr>
<th>Product groups (Stage 1)</th>
<th>Woodwork (BP4.1.1)</th>
<th>Plasticfab (BP4.1.2)</th>
<th>Assemble parts (BP4.1.3)</th>
<th>Spray parts (BP4.1.4)</th>
<th>Prepare mould (BP4.1.5)</th>
<th>Heatform parts (BP4.1.6)</th>
<th>V’forming (BP4.1.7)</th>
<th>Mouding (BP4.1.8)</th>
<th>Release products (BP4.1.9)</th>
<th>Lean assy (BP4.1.10)</th>
<th>Batch assy (BP4.1.11)</th>
<th>Package (BP4.1.12)</th>
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<td>X</td>
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<td>Repeat units</td>
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<td>Rerun or update kits</td>
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<td>Graphic based kits</td>
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</tr>
</tbody>
</table>

**Process based product classification continued**

**DP4 Produce and deliver**

**Product groups**

- Wood work (BP4.1.2.1)
- Plastic fab (BP4.1.2.2)
- Assemble parts (BP4.1.2.3)
- Spray parts (BP4.1.2.4)
- Prepare mould (BP4.1.3.1)
- Heatform parts (BP4.1.3.2)
- V’Torming (BP4.1.4)
- Mouding (BP4.1.5)
- Release products (BP4.1.6)
- Lean assy (BP4.1.7)
- Batch assy (BP4.1.8)
- Package (BP4.1.9)
5.4 Static cost and value stream model of POP Ltd

It was realised from the product classification exercise that products can be suitably classified based on the similarity of their processing needs and also on the work content requirements of the products realised through the same processes. Classifications based on similarity of processes and work contents made it possible to bring together products of similar process requirements, hence reducing the complexities associated with managing high variety products. Results from the process classification exercise showed that the products realised by POP Ltd can be divided into six product families: high standard units, low standard units, high repeat units, low repeat units, update kits, and graphic-only kits.

Based on these classifications, cost and value stream models were created for the different product families. This was achieved in stages. The first stage involved creating a top-level cost and value stream model for the product families. This involved identifying the network of business processes and the associated values and cost they provide for the business. In addition, process realisation times and outputs are flexibly encoded into the model.

At the next stage of the modelling exercise, the static cost and value stream model was used as a reference model for conducting a further static analysis on the business processes of POP Ltd. Figure 7 shows a top-level static cost and value stream model that was developed for this purpose, which graphically represents the top-level POC for generating values and cost for POP Ltd’s six product families. This static cost and value stream model visually describes how information, material, and resources are transferred among the top-level DPs. Initial values of materials representing the material prices for each of the product families are shown at the material inventory point. Also, average production volumes deduced from the sales record are shown on the model. The processing and waiting times for the different product families are shown as a range. For example, 2 days to 3 months is shown as the waiting time for raw-material inventory. This range takes into consideration the least and maximum waiting time in that inventory. To estimate the total value generated for ‘y’ different product types with ‘N’ sales volumes at ‘P’ selling prices, the monetary or sales value is given by the expression:

\[
\sum_{y=1}^{y} p_y N_y.
\]

It was estimated that the ‘value added’ by the production system to raw materials and components, in transforming them into finished goods meeting customer requirements, is the difference between the selling price of the finished goods and the total purchased price of the raw material and components required for production (Agyapong-Kodua et al. 2009). Meyer et al (2007) has shown that the value added is given by:

\[
\text{Value added (for } m \text{ and } n \text{ numbers of flows) } = \sum_{j=1}^{m} p_v_j - \sum_{k=1}^{n} p_i_k,
\]

where \( p_v \) is the value of output product; \( p_i \) is the value of input product; \( m \) is the number of output product flows; and \( n \) is the number of input product flows.

The total value added by the processes of POP Ltd is the sum of values provided by ‘front end domain’ (DM3), ‘produce and deliver domain’ (DM4), ‘manage business domain’ (DM5), ‘support services domain’ (DM8), and ‘product and process improvement domain’ (DM9). Because the focus of the research is on estimating ‘direct value’ through physical manufacturing processes, a decision was taken to limit the cost and value analysis to processes within the ‘Produce and deliver domain’ (DM4). This implies that direct material value addition will consist of three
business processes: (1) ‘make components’ (BP4.1); (2) ‘assemble and pack’ (BP4.2); and (3) ‘despatch finished POPs’ (BP4.3). The value of input product ($p_i$) is the purchase price of all materials and components required for the manufacture and assembly of POPs. $p_i$ was obtained from the price list provided by the purchasing department for the BOMs specified for the different product types. Although a detail-specific value analysis can be conducted based on the individual material requirements, it was more convenient considering the number of products analysed, to estimate an average historic price for materials and parts required to produce the different product families. The total value of output product ($p_o$) is the sum of the sales value for different product families realised over a specific time frame. These data were deduced from the sales and accounting records obtained during the initial stages of the research. At the next level, since the objective of the research was to use values and cost generated by business processes as a basis for recommending process improvements, it was decided to estimate actual values added and cost generated by the individual business processes required to produce the six product families. The end result of these estimates together with the process cost incurred as a result of the realisation of the business processes was indicated on the sub-level cost and value stream model created for the various product types.

To estimate values added by DP4, ‘value estimation indices’ were defined and used for determining the amount of value generated through the realisation of DP4. Basically, it involved determining the resource values of the company and estimating in proportion how different sections contribute to the overall resource value of the company. The degree of value realised through a process is dependent on resources associated with the realisation of the process. Resources, here, refer to humans, machines, and technology necessary to realise the product or service. Another view that was harnessed was that, for sub-business processes, their values can be compared with the selling prices of subcomponents they produce. For example, market prices of similar vacuumformed products can be compared with values generated by the vacform process. Where value indices and hence value estimation at the business process level are impossible, market prices of components are used to compare with process cost so that decisions of make or buy can be explored.

This is, however, not applicable at the domain process level of POP Ltd, since DPs in POP Ltd realise a broad range of products. Hence, the value estimation was limited to the value indices, while at the business process level,
market prices of components were analysed. In most companies, data already exist; especially when valuation exercises have already been carried out. In POP Ltd, the accounts department indicated that the production department (primary manufacturing, assembly, and packing) contributed to 65% of the total value of POP Ltd.

To fully appreciate the importance of the value estimations, detailed cost estimations were made for each business process belonging to DP4. This was to help understand the economic benefits attainable in fulfilling identified business processes in POP Ltd. The proposition maintained in this estimation exercise is that process parameters such as operation times, queue size, setup times, movements, delays, lead times, resource availabilities, and all the lean metrics specified in the published literature as essential for reducing waste contribute to the generation of cost. Hence, process cost estimates were based on conventional lean VSM parameters. The contrast is that in most published literature, such process parameters have been used in estimating values added by processes. However, in reality, these parameters contribute to cost. Thus, in essence, economic value generation depends on a number of other external factors that may be beyond the control of the company, but process cost can be reduced such that the net profit or value obtained by the company is high. In estimating process cost of the business processes in ‘produce and deliver POPs’ (DP4), cost engineering methods and equations as proposed by Son (1991) and modified in Agyapong-Kodua (2009) were deployed. In theory, for a piece of material, \( m \), to be routed through a process class, \( P_{id} \), comprising, \( a_p \) activities (or process steps) that are realised through the application of \( dp \) set of resources, if the overall cost involved in achieving, \( P_{id} \), is \( P_c \), then the process cost can be expressed as a mathematical function of cost parameter, \( c \), involving the factors observed to be contributing to the realisation of \( P_{id} \). Thus:

\[
P_c = c(a_p, dp)
\]  

(Agyapong-Kodua 2009). Also, for a labour-intensive activity described by the model, the actual manual labour that transforms a material piece, \( m \), is defined by

\[
L_d = n_o \times r \times z
\]  

where \( n_o \) is the number of operators; \( t \) is the time spent; \( r \) is the existing rate of pay or wages per time; and \( \alpha \) is a percentage availability factor. It was also decided that indirect labour and benefits where necessary would be added to the labour cost. Thus, if ‘y’ different numbers of jobs use indirect labour of salary \( s \), then for \( z \) numbers of indirect labour units, the total indirect labour cost, \( L_i \) is given by:

\[
\sum_{y=1}^{y} S_y Z_y \ldots
\]  

The total labour cost for a process class, \( P_{id} \), then becomes \( L_d + L_i \). Similarly, for a machine intensive work centre with, \( m_r \), the usage cost of \( N \) numbers of machines, if \( t \) is the total machine usage time, then the total usage cost is

\[
M_u = \sum_{N=1}^{N} m N t N \ldots
\]  

Mathematically, for process, \( P_{id} \), involving \( N \) numbers of machines operating over a period \( T \), the total machine cost, \( M_t \) is:

\[
\sum_{N=1}^{N} \left[(m N t N + m N v N + b N u N) + a f + W \right],
\]  

where \( m \) is the maintenance cost per unit, while \( v \) is the total maintenance time; \( b \) is the repair cost per unit time; \( u \) is the total repair time; \( a \) is the insurance premium rate; \( f \) is the cost of the machine; and \( W \) is the property tax of machine \( N \).

Considering the floor-space cost, if the floor square metre cost is \( f_s \), and the manufacturing floor space is \( M_s \), then the floor-space cost,

\[
C_f = f_s x M_s \ldots
\]  

The storage cost, $S_c$, is expressed in terms of the floor-space cost and the cost of keeping materials in storage over a given time. Thus, for $n_m$ number of materials or components in storage with $C_s$ unit cost, stored over $t$ length of time, the inventory cost, $C_i$, is expressed as: $C_i = n_m C_s t$. Therefore, for $N$ different types of machines with $p$ number of storage points, the total storage cost is expressed as:

$$S_c = \sum_{N=1}^{N} C_{fN} + \sum_{p=1}^{p} C_{ip}.$$  \hfill (10)

In estimating tool cost, $T_c$, assuming a tool has a useful life $n$, then the total tool cost can be expressed as:

$$T_c = C_t N_t \ldots$$  \hfill (11)

where $C_t$ is the unit cost per tool, and $N_t$ is the total number of different tools changed.

The resultant cost and value stream model of BPs 4.1 and 4.2 for realising the six product families is shown in Figure 8.

This BP level cost and value stream model (Figure 8) was linked to the parent model (Figure 7) so that cost and values can be traced. Further analyses on the cost and value contributions of sub-business processes belonging to BP4.1 and 4.2 were carried out by adopting the same estimation principles as described previously. To achieve average values generated for each product family, total values generated by the sub-business process were divided by the total number of products processed through that business process. This was performed for all the product families. In addition, market-price information for similar products obtained for these sub-BPs was compared with the estimated values. The values estimated were found to be less than the market selling prices of similar components; hence the estimated process values were considered to be the limiting factor for efficiency estimation and were therefore used for further analysis. Thinking about the sub-sub-BPs that exist in BPs 4.1 and 4.2, it was

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Figure 8. BP-level cost and value stream model.
realised that ‘vacform parts’ (BP4.1.4), ‘produce moulded parts’ (BP4.1.5), ‘release products’ (BP4.2.1), ‘lean assemble POPs’ (BP4.2.2), ‘batch assemble POPs’ (BP4.2.3), and ‘pack finished POPs’ (BP4.2.4) require no further decomposition to sub-sub-BPs. Instead, these processes are decomposed into their elementary enterprise activities. Hence, at the next stage of modelling, further analysis and cost and value stream modelling were conducted for only sub-sub-BPs belonging to ‘Make prints’ (BP4.1.1), ‘Make wooden and plastic parts’ (BP4.1.2) and ‘Heat bend parts’ (BP4.1.3) processes. In principle, further lower level cost and value stream models can be generated by observing the activities required to fulfil the sub-sub-business processes. Creation of activity-based cost and value stream models will depend on the intention and purpose of the modelling exercise. In reality, since activity diagrams for the sub-business processes were created during the enterprise model development, it is fairly simple to develop activity based cost and value stream models. However, in this exercise, because of the intended transformation of static models to dynamic models, it was not necessary to create detailed activity-based cost and value stream models. Activity-based cost and value stream models were captured during dynamic, discrete-event simulation modelling. The idea presented here is that BPs are realised through the execution of sets of activities defined as elementary ‘activity configurations’. Thus, a hierarchical cost and value stream modelling scheme can be enacted where elementary activity-based cost and value streams are connected to their sub-sub-BP models, which are also connected to their BPs and then to their DPs and DMs. By adopting this approach, modelling elements can be captured in context and analysed within a framework consistent with their application.

5.4.1

Analysis of static cost and value stream model of production system of POP Ltd

A number of static analyses were performed on the results generated by the model. This was to form the basis for recommending improvement on relevant BPs in the POP Ltd production system. The analysis of results described in this section takes into consideration sets of information on inventories and movements in POP Ltd were not captured in the static model. For example, movement and storage costs, which are critical waste indicators, were not captured in the model. This is because data used in the results generation were based on already-achieved products, and it was extremely difficult to estimate inventory sizes, queue times and number of movements between processing stations for the different product families. It was envisaged that in the creation of dynamic cost and value stream models, these process variables can be generated automatically when processing and completion times are assigned in the model. Some of the useful analyses are described in the subsections that follow.

5.4.1.1 Cost and value analysis of BPs. A summary of the direct operational cost and values generated by key BPs realising Unit A is shown in Figure 9. From the summary results, it can be seen that for Unit A, ‘vacform parts’ (BP4.1.4) and ‘produce moulded parts’ (BP4.1.5) generate high values. On the contrary, operational cost exceeds value generated for ‘develop screens’ (BP4.1.1.1), ‘screen print manually’ (BP4.1.1.2), ‘auto screen print’ (BP4.1.1.3), ‘produce wooden parts’ (BP4.1.2.1), ‘fabricate plastics’ (BP4.1.2.2), ‘assemble parts’ (BP4.1.2.3), and ‘spray parts’ (BP4.1.2.4) processes.

Similar results were obtained for Units B, C, and D. Studying the summary results of cost and values generated during the production of Update kits, it was noticed that in addition to the processes whose operational cost exceeded their values generated, for Units A, B, C, and D, three more BPs produced parts at a higher cost than their...
values (Figure 10). These additional processes were ‘prepare mould’ (BP4.1.3.1), ‘heat form parts’ (BP4.1.3.2) and ‘make polydromes’ (BP4.1.1.8).

5.4.1.2 Comparison of values realised by product families and business processes. Based on ‘as-is’ operations of POP Ltd and 6 months of sales records, Figure 11 shows that for single products belonging to each of the product families, Unit A generates the highest value of 24%, while Update and Graphic only kits generate the least unit value of 9%.

Units C and D also provide reasonably high values of 22% and 21% respectively. This implies that when more orders of Unit A, C, and D are produced, POP Ltd is likely to accumulate high values. However, a study of the production pattern of POP Ltd shows that for the production period specified, graphic-only kits contributed 36% of the total value generated, while Units A and B produced the least values of 8% each (Figure 12). This is because, within the period of study, POP Ltd produces high volumes of graphic-only kits and lower volumes of Units A and B. If this trend remains, efforts will have to be made to reduce the cost involved in producing graphic only kits so that more profits can be realised.

Summing the values realised by sub-sub-BPs and assigning them to their corresponding top level BPs, it was observed that for all the product families realised, ‘vacform parts’ (BP4.1.4) and ‘produce moulded parts’ (BP4.1.5) generated the highest values. At first glance, it appeared they were the most essential processes that should be focused on, since their cost concentrations were low. However, further discussions with managers of POP Ltd gave different indications.

6. Observations and conclusions

6.1 Observations and recommendations on POP Ltd operations

When reasoning about cost and value streams in POP Ltd, it was observed that although Unit A required the longest processing time, the sale of Unit A generated high values. Hence, on the basis of revenue generation, POP Ltd may need to produce more of Unit A (Figure 10).

Collectively, graphic-only kits generated the highest production value. This is basically because of the high production volumes of graphics-only kits realised. Also, among BPs identified in the production processes of POP Ltd, vacforming and moulding operations tend to possess the capability of maintaining high values for all product families in POP Ltd. Although, in theory, this was the case, the managers of POP Ltd indicated that vacform and moulding processes are the highest producers of excess inventory and major contributors to overstocking in the company. It is therefore difficult to conclude that vacform and moulding processes make the highest value
contribution to POP Ltd. From the results presented, although storage and movement cost have not be added, it is however clear that it is expensive to ‘make wooden and plastic parts’ (BP4.1.2). This is because the cost realised by the sub-sub-BPs exceeded the values they contributed. Also, for all products apart from graphic-only kits, cost generated by ‘develop screens’ (BP4.1.1.1), ‘screen print manually’ (BP4.1.1.2), and ‘auto screen print’ (BP4.1.1.3) processes were higher than the values they produced (Figures 8 and 9). Hence, potentially, these processes need to be redesigned for better cost, or further investigations will be required to assess the possibility of buying parts or outsourcing these processes.

To derive ‘to-be’ models of POP Ltd with better cost and value indicators and also to investigate how production flow and production techniques such as push and pull can be introduced into POP Ltd’s production system, it will be necessary to convert the static models into dynamic simulation models. In the static model, resource utilisation and the impact of resource efficiency on cost and value generation was not analysed. This was because of the enormous amount of data that would have been dealt with manually. Generally, production systems must be designed to operate effectively at different operating workloads. However, alternative workloads and associated dynamic instances of processes cannot be visualised readily and effectively in the static model. Also, to satisfy the requirements of POP Ltd to redesign their processes to reduce process inventories and production lead times, introduce flow, and improve resource utilisations, which are key cost improvement schemes, the second phase of the methodology, which involves the integrated use of system dynamics and discrete-event simulation models, has to be created and used to test various alternative business scenarios.

6.2 General observations and conclusions about the static cost and value stream modelling methodology

This paper has described how the multi-product cost and value stream modelling technique was enacted to capture relevant process data, create models with data captured, and analyse results derived from the model. The method demonstrated how multiple high-volume product flows can be simplified through a process-based classification. Identification of process similarity ensures that products following similar processing routes are grouped together. Further segregation of products with similar process properties was achieved using a work-content approach to process-based classification. This ensured that a wide variety of products were grouped into six different product families, hence limiting complexities associated with managing large product types. Although there might be some differences in products belonging to the same family, these differences were considered to be minor.

The approach introduced a means of identifying networks of processes involved in the realisation of specific product families giving room for detailed process-product based analysis, planning, and improvements. This was necessary to discern process routes and hence provide a better means of analysing multiple products. Most importantly, because processes were decomposed from parent processes to their minute activities, a rich understanding about how processes are interconnected and how materials, resources, and information are transferred across process segments was gained. The hierarchical approach to modelling cost and value streams ensures better understanding of processes, therefore providing an enhanced means of analysing cost and values generated through the top or down. Because the cost and value stream modelling technique depends on enterprise modelling, for companies already involved in the use of enterprise models, the application of the cost and value stream modelling technique will be most suitable. However, for companies without any knowledge of the creation and application of enterprise models, additional work will be required to create enterprise models that will form the basis of the modelling technique. One added advantage through the use of this technique is that once first-stage enterprise models are created, other benefits associated with the use of enterprise models, such as improved communication among functional entities in companies, instrumentation of business process re-engineering, and managing system complexities, among others, can be obtained. The challenge, however, is that a large amount of time is always required to create a fairly representative enterprise model. An improvement in the technique is perceived along the lines of decomposing only relevant processes of interest when the desire is to conduct a cost and value stream analysis of business processes.

One of the key outcomes of this paper is the introduction of a method of estimating real values added by business processes. Previously published literature on value streams, especially within the lean school of thought, essentially maps lead times, cycle times, and delays, and uses these metrics for specifying value-added and non-value added processes. It has been observed that most often, process variables such as cycle times, delays, queue sizes, and lead times rather affect process cost and not value. It was shown that real economic value achieved by a company is dependent on selling prices of products and production or sales volume. These two factors, coupled with the value of
resources required to achieve production, provide a means of estimating values added by individual business processes. Based on these indications, it can be said that, in reality, improving company value generation goes beyond internal company operations. Competitive prices, market trend, customer preferences, and other factors that affect the sale of products also affect value generation. However, for higher profits, efforts must be made to reduce process cost by cutting down on operation times, resource and material cost, movements, and storage cost. This is because these latter factors affect the cost of production, and so when they are reduced, high profits can be generated, even if the values derived do not change. Process redesign is therefore vital to ensure that key process metrics are reduced where they have a positive influence on cost.

Comparing the modelling technique with the best literature representation of VSM, it can be seen that additional constructs have been introduced. It was observed that between processes, it was necessary to indicate what was transferred. Thus, a construct was introduced to represent physical resources that flow between processes. Also, a construct was introduced to represent human resources required for process centres. Also, to enhance the cost and value stream modelling formalisms, further modelling constructs were introduced to represent ‘information’ and ‘finance’, where those constructs were borrowed from the domain of enterprise modelling. However, the static model does not show exactly the type of human resource or physical resource required by process centres. To indicate the type of inventory as well as queue sizes and queue times, a new construct was also introduced. These new constructs enriched the cost and value stream model, making it more informative and comprehensive.

During the test of the applicability of the modelling technique in the case company, it was observed that the proposed multiproduct cost and value stream modelling technique is capable of:

1. Modelling multi-product flows in complex manufacturing environments. This is based on proper process-based product classification.
2. Defining and estimating values and cost generated by business processes, and using these economic indicators to specify processes that are inefficient and hence requiring re-engineering. Process analyses are further conducted to generate ‘to-be’ manufacturing systems models with better cost and value indications.
3. Decomposing processes into their elementary levels such that processes can be chained to their parent processes for detailed analysis and observation of changes in processes and their impact on other processes, resources, and outputs.

In Section 2, requirements for multi-product cost and value stream modelling were specified for MEs realising multi-product flows. Different process mapping tools, EMs, and SMs were assessed against these modelling requirements. Among the tools, VSM was considered to be a useful tool but had limitations in analysing processes realised by MEs engaged in multiple product flows. It was proposed that VSM could be enhanced to provide needed solutions in multi-product flow business process designs and analysis. In view of the limitations of the VSM technique, the CIMOSA modelling technique was enacted to support VSM especially in its decomposition formalisms and non-determinisms in model generation.

When the end benefit of alternative process designs and analysis as well as meeting CIM requirements was considered, iThink and Simul8 simulation modelling were considered useful to support the modelling schemes specified. Future work and publications will demonstrate how these simulation modelling techniques are integrated into the technique described in this paper to help:

1. Model aspects of complexities and dynamics in processes in an ME such that causal and temporal effects of changes in process states can be visualised, controlled, and managed to ensure that MEs remain stable within their lifetime.
2. Conduct experiments on business ideas, scenarios, and process improvement suggestions to determining best options before their implementation. This has the enabled benefit of facilitating process (re) design and optimisation.

References


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