Process Control Parameters Evaluation Using Discrete Event Simulation for Business Process Optimization

Parminder Singh Kang[1], Adam Aboutaleb[1], Christopher Ugo Silva[2], Alexandre Erhart[3], Victor Todeschini[3] and Alistair Duffy[1]

[1]Advanced Manufacturing Processes and Mechatronics Centre, Faculty of Technology, De Montfort University, UK, LE1 9BH, +44-116-257-8089, Email: pkang@dmu.ac.uk, aaboutaleb@dmu.ac.uk, apd@dmu.ac.uk

[2]M Wright and Sons Ltd., Quorn Mills, Leicester Rd, Quorn, Loughborough, LE12 8FZ, +44-1509-412365, Email: CSilva@mwright.co.uk

[3]NEO Industrial Engineering Email: alexandre@neoep.com.br, victor@neoep.com.br

Abstract

The quest for manufacturing process improvement and higher levels of customer satisfaction mandates that organizations must be equipped with advanced tools and techniques in order to respond towards ever changing internal and external customer demands by maintaining the optimal process performance, lower cost and higher profit levels. A manufacturing process can be defined as a collection of activities designed to produce a specific output for a particular customer or market. To achieve internal and external objectives, significant process parameters must be identified and evaluated to optimize the process performance. This even becomes more important to deal with fierce competition and ever changing customer demands. This paper illustrates an integrated approach using design of experiments techniques and discrete event simulation (Simul8) to understand and optimize the system dynamic based on operational control parameter evaluation and their boundary conditions. Further, the proposed model is validated using a real world manufacturing process case study to optimize the manufacturing process performance. Discrete event simulation tool is used to mimic the real world scenario, which provides a flexible and powerful way to comprehensively understand the manufacturing process variations and allows controlled "What-If" analysis based on design of experiments approach. Finally, this paper discusses the potential applications of the proposed methodology in the cable industry in order to optimize the cable manufacturing process by regulating the operational control parameters such as dealing with various product configurations with different equipment settings, different product flows and work in process (WIP) space limitations.

Keywords: Business Process Optimization, Design of Experiments, Discrete Event Simulation, Process Control, Continuous Improvement.

1. Introduction

Business processes are becoming more and more complex due to the increased variability in the business processes, often induced by complex interdependencies exist between business process activities and their operational control parameters and high product variety. The management of modern business processes is an arduous task, because of the mutual relationships between the different business processes of an organization and associated physical systems. This makes the process improvement initiatives, even more difficult because 1) it is difficult to quantify and analyze the behavior of complex business processes using existing tools and techniques and 2) there is a lack of understanding how simulation based approaches can be used in a structured and systematic manner [1, 2 and 3]. This even becomes more important to deal with fierce competition and ever changing customer demand. This paper illustrates an integrated approach using design of experiments techniques and discrete event simulation (Simul8) to understand and optimize the system dynamic based on operational control parameter evaluation and their boundary conditions. These operations control parameters can be controllable or uncontrollable. Controllable parameters can be controlled by an organization or process owners, such as, machine speed, job sequence (especially make to stock), number of operators, etc. On the other hand, uncontrollable parameters for a process are derived by its customer and in most cases these cannot be changed (or need to pay penalty for any changes to these), for example, due dates, quality levels, etc. The overall methodology is developed on the idea of multidimensional construct, where the DES model is integrated with design of experiments (DOE) method for quantitative analysis in order to analyze and optimize the system behavior. This paper is organized as; the second section provides a literature review in order to provide brief background about business process, various modeling techniques and introduces the DES. In the third section problem definition is provided from the operational control parameter perspective and the fourth section illustrates the structured business process modelling approach for operational parameter optimization. Further, case study and cable industry relevance is provided in the fifth and the sixth segment respectively. Finally, the conclusion is derived to illustrate the findings and future work.

2. Literature Review

This section introduces the business process and DES to exemplify the business process modeling aspect of research paper. It is important to note that before applying any improvement and optimization approaches, the process boundaries must be identified as a part of the improvement plan. Therefore, this segment illustrates the business process attributes to define the process boundaries and modeling aspect to establish which approach can be used and DES to model the real world.

2.1 The Business Process

It is important to understand the components of a business process before trying to improve or optimize one. A business process is the combination of a finite set of activities within an organization that are executed according to rules or policies in order to achieve certain goals (Figure 1). The overall idea is to achieve these goals by transforming the different kinds of input to an output that is regarded as value to the customer [4]. According to Zairi [5], it is the way in which all the resources of an organization are used in a reliable, repeatable and consistent way to achieve its' goals and the performance is measured against the organizational goals through agreed key performance indicators (KPIs). Some common examples are product development, production, service delivery, customer strategy & relationships, etc. Business process exhibits the following features [6 – 7];

- **Goal**; provides a justification for the business process existence or performing an activity. For instance, goal of manufacturing process could be increased throughput, reduce waste, reduce lead time, etc. The organizational goals often determine the improvement and process optimization initiatives.
- **Definable Inputs**; inputs are the most important aspect of a business process, not only to produce a desired output but for the process improvement and optimization. It is mainly in the form of; 1. Raw material; which is transformed into a product according the customer specifications, 2. Information; from customer, supplier and succeeding/proceeding activity to provide the desired output specifications, raw material attributes (quality, quantity, cost, quality, cost, etc.) and control information respectively.
- **Desired Outputs**; expected output mainly as a part of customer expectations. This is measured in the form of KPIs and provides a quantifiable mean to customer expectations. For instance, throughput (number of units to be produced of product "X"), lead time, waste, etc. It also provides a measure against the goal and measure for the process performance.
- **Events**; defines a trigger for an activity or whole business process. The event may be consumed or transformed or act as a catalyst. For instance, what to produce next based on the current process state and customer requirements or which operation to schedule next once the current operation is finished.
- **Resources**; a resource is a necessary mean for executing an activity. Resource might have a specific or multiple roles to execute specific activity or activities respectively. For instance, production planner, machine operator, supervisor for documents sign off etc.
- **Activities and their Dependencies**; a business process consist of well-defined interdependent activities, which transforms the inputs into desired output via a logical flow of these interdependent activities. For example, a "Purchase Order" process consists of three activities i.e. 1. Process paper request, 2. Generate purchase order and 3. Receive shipment. These must follow a logical sequence to deliver end-to-end value. However, all activities may not add equal value to the process.
- **Creates Value**; the overall aim is to create value from a customer perspective, which may be end customer from the supply chain perspective or an intermediate based on the activity/process interrelationship. This is measured based on the KPIs and goals.

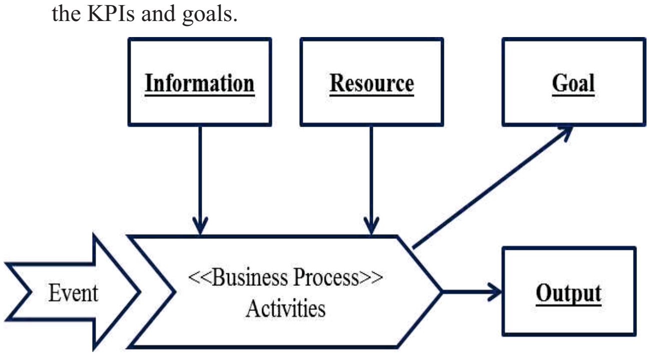

Figure 1. The Business Process

2.2 Business Process Modeling (BPM)

Business process modeling plays a major role in the perception, understanding, manipulation and optimization of business process. There are a number of tools that are used by researchers for business process modeling. Based on the behavior and interactions, business processes can be classified into four main categories [1 and 2],

- **Deterministic System;** This aspect accords with many structured processes found in stable manufacturing –type environments. These consist of sequence of fixed well defined activities that convert the inputs into outputs to accomplish clear objectives. For instance, order fulfillment, fast food processes, back office processes, etc. From a BPM perspective static approaches are used to map and document the flow of items, activities and their logical dependencies. Some of the commonly used tools are, process flow charting, IDEF0 and IDEF4, data flow diagram (DFD), role activity diagrams (RAD), customer-supplier protocol, etc. Static models provide simplified representation of business process at a particular point in time without capturing the dynamic system behavior, which could change due to the system constraints, uncertainties and mutual interactions between operational control parameters and activities.
- **Dynamic Complex System**; This viewpoint emphasis on the complex, dynamic and interactive features of a system, where the system view involves inputs, transformation, outputs, interrelationships between activities and external interactions with other systems. For instance, a manufacturing system consists of several processes, which interact with each other within the defined boundaries, such as drawing, cabling, jacketing, etc. These can be optimized based on the manufacturing operational control parameters within the system boundaries under investigation. However, from the organizational perspective, optimal operation of manufacturing system depends on the inputs and interaction with other systems, such as customer management, raw material supplies (supplier system), etc. In other words, the idea is to create an end-to-end value instead of improving operations locally. In order to consider the external interactions, this view stresses the understanding and analysis of the system as whole instead of individual components. Discrete event simulation (DES) and high level Petri nets are two main approaches identified to model such systems. DES modeling provides more efficient and flexible way for system modeling and 'What-If' analysis to improve and optimize the business process. Along this, DES tools are equipped with visualization capabilities, to illustrate the proposed system changed. Despite the advantages of dynamic modeling and visualization capabilities, it is still difficult to model the human behavior (resources) and as the system complexity increases the time and cost required to model such a system also increased.
- **Interacting Feedback Loops**; This perspective extends on the previous two approaches by providing the closed loop control based on the internal structure and policies. The flow of input to output transformations is regulated using explicit decision points based on the feedback loops. An action can be triggered when actual and desired outputs don't match for a given KPI. From the system dynamic view point, combining the feedback loops with deterministic modeling techniques provides a qualitative analysis to understand the system stability and behavior, whereas dynamic modeling techniques quantitative analysis to determine the effect of decisions on the system under investigation. Kang el al [8] provides an example of

such environment where the scheduling rule is chosen from a given rule library based on the current system state, unscheduled jobs, KPIs and user defined control variables. In this case, the system is modeled using Preactor 500 APS software and linked with an autonomous scheduling module to support the informed decision making.

- **Social Constructs**; This focuses on the subjective and the human aspect of the business process based on their meanings, abstractions and judgments about the real world. For example, an order fulfillment process can be perceived differently by production and marketing manager as products manufactured on time and customer satisfaction respectively. It is identified that this approach fits well with strategic, less tangible business processes, where human activity is a major driver. For example, healthcare, social, educational, etc.

Further, modeling can be classified based on [9];

- **Purpose of Use**; the sole purpose of modeling is not just improvement and optimization. Based on the purpose of use, it can be; 1) Descriptive modeling for learning, 2) Decision support for process development and execution and 3) Ability to provide an enhanced support.
- **System Behavior**; this is an important aspect to decide on which tool is best to model the given system i.e. 1) Active; possesses the dynamic modeling ability and provides support for the user interactions, for example DES and 2) Passive; diagrammatic representation of a system with no capability to support the user interaction and dynamic behavior, such as RAD and DFD.

Vergidis et al. [1] argue that there is an abundance of business process modeling techniques that only capture and address the different aspects of business process, however, very few provide quantitative analysis and optimization capabilities to enable structured process improvements. From the research perspective, the model will be used to understand and optimize the system behavior in order to derive the improvement initiatives. Also, system under investigation exhibits the properties of a complex system. Therefore, DES was selected as a modeling tool for this problem.

2.3 Discrete Event Simulation (DES) Approach

DES is a form of computer-based modeling that provides an intuitive and flexible approach to imitate the behavior of complex systems. It provides a structured environment to understand, analyze and optimize the complex business processes [10]. Simulation approach is regarded as indispensable problem-solving methodology for the solution to many real-world problems. It allows the analysis of actual system through "What-If" analysis [11]. Most of the real world business process improvement problems are complex and combinatorial in nature i.e. simulation is must to analyze such systems. Aguilar-Saven [6] classifies the simulation modeling techniques based on the;

- **Input Data;** this can be either fixed or randomized representing the deterministic or stochastic behavior of the system respectively.
- **Time;** either dynamic where time plays an essential role or static where time has no role.
- **System State;** system state changes at a specific point based on certain event i.e. discrete or system state changes continuously i.e. continuous.

Therefore, based on above illustration the system under investigation exhibits the stochastic behavior with time as a key element and system state changes with respect to discrete intervals. Hence, DES is chosen as a tool to model the system behavior.

The basis of DES modeling is formed based on the three aspects i.e. System, Model and Simulation, which can be exemplified as [12];

- **System**; represents the real world business process, which operates in space and time. In this case business process refers to the dynamic complex system.
- **Model**; is simplified representation of the system at some point in time and space, which is similar to the system but simpler. However, it must include most of the salient features of the system to represent the problem closer to reality. Based on the arguments provided in Section 2.2, DES is used to model the system.
- **Simulation**; allows manipulation of a model (System) and analysis of interrelationships of processes and associated constraints in the time and space, i.e. "What-If" analysis that would not otherwise be apparent in the real world.

From the business process control parameters evaluation aspect many of business processes have similarities and there are numerous examples where simulation is applied successfully to solve these problems. For instance, optimization of twisted-cables manufacturing process using a structured approach based on IDEF0, DES and DOE approach [13], understanding the production process dynamics for engine refurbishing plants for US Air Force to standardize and optimize the operations [14], to validate the future state for a Lean transformation process by including the time based random variability for different processes [15 and 16], to reduce the setup time for sheeting operation in pulp and paper manufacturer scenario [17] and to optimize the JIT production process for automotive component-manufacturing environment by investigating the effect of system constraints on production environment [18]. Ghasemi et al. [3], provides a comprehensive list of simulation applications in different systems, for instance, 1) production systems to design, location optimization, capacity and resource management, 2) transportation systems for evaluation and planning of rail, road systems, 3) communication systems, such as air traffic control, evaluation and performance assessment of terminals [26], 4) production control and management for planning and scheduling [8], 5) financial systems for risk and cash flow analysis, 6) environmental sciences to understand the energy usage, food and pollution control and 7) ergonomic for instrument management, faulty layout design, workforce planning and organization relationship evaluation.

However, most of the approaches lack a systematic methodology to guide problem solvers/decision makers throughout the optimization and improvement processes [1]. There are a number of advantages using DES modeling, which can be given as [10, 17, 19 and 20];

- Through modeling observing the system's operation in detail over long periods of time a better understanding of the system of interest.
- Hypothesis testing, Investigating new operations, procedures, rules and flow.
- The flexible modeling approach provides a simple illustration of complex systems by considering the stochastic influences.
- The opportunity to exploit system constraints to measure the effect of variability on KPIs. Therefore, provides an

opportunity to analyze the business process with consideration to their dynamic characteristics.

- Understanding of system constraints, bottlenecks and uncertainties.
- Provides a systematic problem solving approach and business process optimization, especially by investigating using number of experiments i.e. "What-If" analysis.
- Training and visualization.

3. Problem Definition – Operation Control Parameters

The purpose of this research is addressing the business process optimization problems in general by evaluating the process control parameters. However, by considering one of the most important characteristic of "Operations Research" study i.e. investigation of problems in context of its system orientation. This means that the an activity by any part of the organization has some effect on the other part of an organization, in fact, optimum operation of one part of system may not be optimal for another part. For instance, a production department may be interested in long, uninterrupted runs of production runs since they reduce the setup and cleanup costs. Therefore, solving production planning problems from this viewpoint is really simple. Conversely, these long runs might cause other issues, such as large raw material, in-process and finished product inventories, which might not be the preferable choice for other departments. Therefore, to evaluate any decision regarding process improvement or optimization, one must identify all possible interactions and determine their effect on the system (organization) as whole.

Based on the above, the methodology is validated on a carbon fiber manufacturing line by considering the system as whole. The carbon fiber line is investigated to maximize the throughput and resource utilization and minimize the cost (See Derails in Section 6). However, this problem can be generalized based on the generic business process and its attributes (Figure 1). In other words, the main problem addressed in this paper is to minimize the effect of variability by adjusting the operational control parameters. Therefore, the solution proposed using this methodology can be used to solve the operational problems as long as the system is represented using simulation models and operation control parameters are identifiable.

4. Structured Business Process Modeling

As discussed in the Section 2, most of the BPM approaches don't follow a structured approach and lacks the ability to support the decision making process through quantitative analysis and optimization. The main aim of this section is to illustrate the proposed systematic and structured (Figure 2) approach to overcome the drawbacks of existing approaches.

1. Business Process Selection; the process starts with the selection of a business process needs to be improved or a problem to be solved. Therefore, all the information related to the system needs to be captured correctly, such as inputs, resources, outputs, constraints, activities and their interrelationships, policies, etc. In order to make the data collection process efficient and simpler, the data is collected based on the following steps;

- **Scope and Objective;** the idea is just to model system under consideration not the whole world, therefore, defining scope and objectives play a crucial role to provide direction for improvement initiatives. Scope here identifies the system under investigation and its' boundaries. The objectives are to quantify the outcome of the improvement initiatives. Therefore, objective related data needs to be collected before and after business process optimization, for instance, scrap rate, throughput rate, etc.
- **Activities and interrelationships;** a business process consists of a number of sub-processes or activities, which are transforming given inputs to outputs. As discussed earlier dealing with time dependent stochastic system needs activity timings (processing time, setup time, failure and repair time) and associated distributions need to be captured. Along this, the sequence of activities plays a crucial role to understand the system behavior based on the interrelationships between the succeeding and proceeding activities.
- **KPI;** KPIs allow quantifying the system behavior based on the given inputs. With respect to KPIs following information is captured; 1) KPI name; to identify what results are collected; 2) Unit of measure and 3) Tolerance limit; provides a decision point if KPI goes out of set tolerance limit and to priorities the KPIs in case of multi-objective optimization.
- **Constraints**; this is one of the most important aspect of BPM, as constraints not only defines the system limits, but also play a key role in the design of experiments. In the proposed methodology constraints are seen as a source of variability, for instance, varying the machine speed between 10 RPM to 20 RPM will have an effect on the quality of the final product. Therefore, from operational parameter control view point system behavior will be tested between these machine speeds based on quality as a KPI. In other words, the experiments are designed based on the constraint values. For constraints following data is collected; 1) Constraint name and 2) Value (Maximum 5 values are allowed per constraint). In fact, constraints are the control parameters and used to generate the set of experiments for analysis.
- **Association Level**; association level links with both KPI and constraints. The whole idea is to define if constraint and KPI are related to an activity or whole system. For example, 1) product quality, throughput rate seen as system level KPIs whereas queue size is local level i.e. associates with a particular activity and 2) Similarly, machine speed and max queue limit are the example of local level constraints. On the other hand, the total number of available resources and different types of orders to be manufactured both are system level constraints.

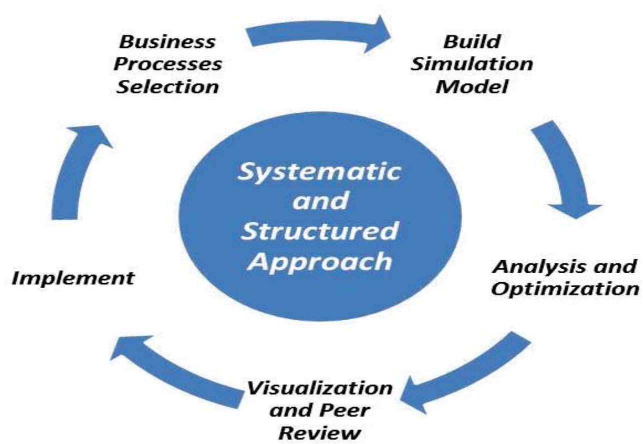

Figure 2. Business Process Optimization

2. Build Simulation Model; the main aim of this step is to conceptualize the business process information to DES model. DES is capable of modeling randomness, uncertainties and stochastic nature of the system, such as variable processing times, routing, etc. In the Current research used the Simul8 package, which provides both modeling and visualization capabilities. In order to validate the simulation model several meetings with process owners and managers were held. For detailed modeling information, please refer to the earlier published work [25].

3. Analysis and Optimization; the overall aim of using DES for modeling is to collect the quantitative data for selected KPIs to analyze the system and optimize its' behavior based on given constraints. The following steps are followed for analysis and optimization;

- **Design of Experiments**; experiment set is generated based on the constraint values. Taguchi orthogonal arrays and full factorial approach is used to study the system behavior. Results are collected with respect to each experiment.
- **Causal Relationship Analysis**; using the results from the previous step a causal relationship analysis is done to understand the system behavior based on given variability levels.
- **Optimization**; optimization is done based on the insights obtained from causal relationship analysis and the KPI tolerance limits defined during the data collection process.

4. Visualization and Peer Review; once the system is optimized, the results and new system state are disseminated to stakeholders for review and approval before implementation.

5. Implement; this includes the real life implementation of an improved system.

5. Case Study

The case study is based on a collaborative project with a UK-based company specialized in manufacturing of woven fabrics and other textile products. The scope of investigation within the company is a new line for the production of carbon fibers. The main Objective of BPM is to optimize the operational settings in order to maximize;

- **Throughput**; the overall objective is to maximize the number of carbon fiber products delivered per year. In the case study it was presented by the number of products delivered during the reporting period.
- **Resource Utilization**; maximize the utilization of available resources.
- **Minimize Cost**; the operational cost for running the production line with the investigated operational settings and number of resources for the production of customer orders as per their specifications.

Like any other manufacturing system, carbon fiber manufacturing process consists of several activities having varying degrees of interdependencies between them (Figure 3). The production starts with an initial design of the fabric manufacturing according to the customer specifications; the required materials are then retrieved from the warehouse and rewinding and mechanical tests are performed upon them. In the meantime, the design is finalized and coupled to the mechanical performance. Afterwards, the creel and loom loading are performed before the fabric production takes place. Finally, the fabrics are optimized and finally inspected before dispatch to customers.

Three resources are operating within this production line; Fabric Designer, Trained Operative and Weaver. Each one of the processes requires a specific resource to be completed apart from the fabrication process which can be performed by either the Fabric Designer or the Weaver.

In terms of constraints the processing time of activities are the properties of;

- **Customer Specifications:** defines the type of fabric and width to be used. For instance, there are 9 types of fabric and width can be 25, 75 or 150 nm.
- **Operational Control Parameters:** varies according to the product to be manufactured**.** These include;
  - **Number of Weaving Head**; 1, 2, 4 or 8.
  - **Number of Rewinding Heads**; 2, 4 or 6.
  - **Loom Speed**; 300 or 700 insertion/min
  - **Sequence Method Used for Creel Loading**; line by line or shortest route.

Some of these constraints are independent while the other performs only a link between the independent factors and processing times. However, constraints exemplified above were given the most attention in this paper as they control the production processes. Though these factors are the main ingredients for operations, the first factor customer specifications are derived from the customer requirements, therefore cannot be controlled by the process owners. Operational settings are considered as controllable factors and are investigated to satisfy the selected objectives. Resources were also examined in terms of the feasibility of hiring weavers and the effect of this on the performance measures.

Following the proposed methodology Step 1, data were collected from the process owners through several meetings. A simulation model was developed using Simul8 modeling package and the simulation time was set to 3 months (a quarter) and the working shifts were defined within the model. From the analysis and optimization perspective, quantitative data are generated form simulation model based on selected KPIs. Therefore, Full Factorial DOE was applied to the operational control parameters

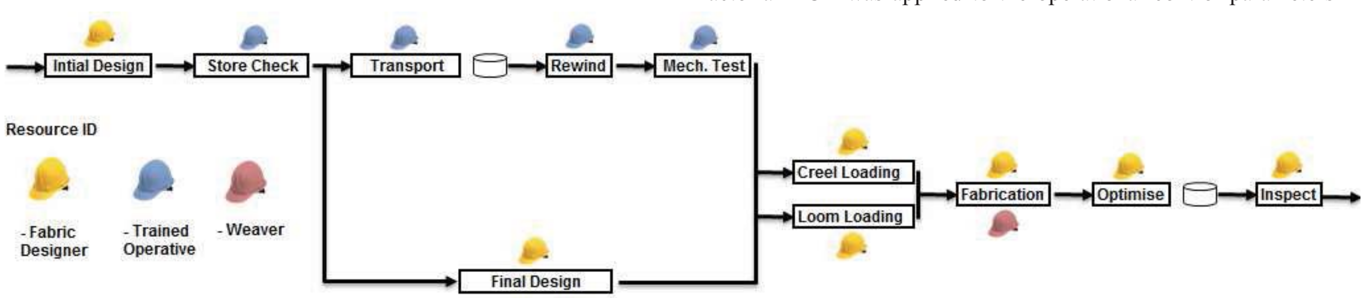

Figure 3. Carbon Fiber Manufacturing Process

in order to generate a list of all possible scenarios that could occur within the production line under investigation. The model was then linked to the DOE and they were used to analyze the impact of the independent factors on the KPIs of interest.

Based on the analysis of results, the following main decision-support recommendations were generated:

- Increase of number of weaving heads is not recommended.
- The addition of more rewinding heads can improve the throughput rate and weaver utilization at the cost of reducing the trained operative utilization.
- No considerable advantage can be achieved by increasing the loom speed.
- The optimum number of weavers is 1; increasing the number to 2 has nearly no positive effect.
- The optimized creel loading sequence method ‘Shortest Route' is highly recommended as it can produce an improvement of 88% in the throughput rate.

6. Wire and Cable Industry Relevance

According the Kang et al. [8] cable industry is also affected by the increased process variability and complexity and competition in global markets. From the operational control parameters aspect, it is spread sheep based models and employs; intrinsic knowledge solely cannot be used for the business process analysis and optimization. Mahfouz [13] exemplifies the complexity of a twisted pair cable (TPC) manufacturing process based on the different product characteristics required according to customer specifications, such as cable type, diameter, number of pairs and length. Changing these parameters influence product flows, equipment operational settings, and product dispatching and create complex interrelationships between manufacturing system operational parameters. To deal with the complexity introduced by complex interrelationships, manufacturing systems are often analyzed based on bottleneck or critical operation and the rest of the process are scheduled around bottleneck [21]. However, these approaches doesn’t improve the manufacturing process due to the high level of variability induced by high product variety, mixed model production, demand fluctuation, product families and customer priorities [21 and 22]. A top level view of a cable manufacturing process can be generalized in the following order; Customer Demand, Logistics and Planning, manufacturing and Delivery. From the business process modeling aspect the key elements are exemplified in Table 2. It is important to note, the subsequent business processes are related in terms of input, output and control parameters. This makes the system behavior complex and stochastic due the interrelationship between not only processes but also the parameters controlling these processes.

*It is important to note that this paper illustrates a generic cable manufacturing process. For consistent quality control, some companies might use intricate quality control measures during every step, which is out of scope of this paper.

Table 2. Business Process Elements

Business Process	Input	Operational Control Parameters	Output
Customer Demand	- Sales Order	- Arrival time, - Manufacturing process capability, - Product list	- Compiled demand list
Logistics and Planning	- Compiled demand list, - Supplier - Product Specifications	- BOM, - Operational Parameters (capacity, resource availability, planned maintenance) - Product specifications (due date, priority, etc.)	- Schedule
Cable Manufacturing	- Schedule, - Raw Material, - Production Order	- Operational Parameters (capacity, resource availability, planned maintenance) - Product specifications (due date, priority, etc.)	- Finished product
Delivery	- Finished product	- Due dates - Customer input	- Customer satisfaction

1. Manufacturing Process;

The main concern of this paper is to look into the manufacturing process, therefore, the generic manufacturing process activities, inputs, operational control parameters and outputs for a TPC are can be given as [13, 21, 22 and 23];

- **Customer Order**; it is assumed that customer order is received and a production list is compiled based on the input and control parameters identified in Table 2.
- **Drawing**; this is one of the key processes that can affect the quality of the final product. For instance, the difference between 23 (0.0226”) to 24 (0.0201”) AWG is only 0.0025”. Initially the diameter of copper rod is 0.3” and copper rod is drawn to take its’ diameter down to 0.09”. It is further drawn down again based on the product requirements.
- **Extrusion**; this is a process of costing the copper conductor with a thin layer of plastic to control the transmission parameters by providing the separation between conductors. The quality of the extrusion process depends on the plastic raw material, temperature and crosshead pressure.
- **Banding**; the solid-colored insulated conductor is banded with white conductor of matching color.
- **Twisting**; pairs are created using twining machines by setting it precisely on different lay lengths, which is an important factor to alleviate the crosstalk.
- **Cabling**; once the pairs are combined, then four pairs are combined using cabling machines. Again, pairs need to be placed properly to control the crosstalk, not only between pairs, but also between cables.
- **Jacketing**; jacketing process is similar to the extrusion process. In this case, jacket thickness is one of the important parameters to determine the compliance with the manufacturer’s procedures.
- **Packaging**; usually packed standard 1000-foot length/box, however, can be longer or shorter.
- **Final Inspection**; before leaving the manufacturing facility, cable is tested to make sure it meets or exceeds the electrical standards set by the standards.

2. Operational Control Parameters;

Specifically, from the TPC manufacturing process perspective, the main inputs to the system are the product specifications and raw material. The complexity comes from the operational control parameters aspect, which creates the interdependencies between both activities and control parameters, which can be given as;

- High variety just based on the variation from four basic attributes i.e. cable type, cable diameter (for TPC for example 0.4, 0.5, 0.6 ad 0.9), number of pairs (for instance 20 types varying from 2 to 1500) and cable length (determined from customer demand). According to Matias et al. [24], based on these product variations cable manufacturers to deal with at least 160 different products for each cable length.

- Alternative routes and resources, for instance, incoming cables for twisting operation can be clustered according to the required cable number of pairs and each cable group follows a different route for twisting operation.
- Setups are required due to material or product changes. This can vary from switching between different products. Other examples are setup due to a material change for extrusion and jacketing process.
- Shared resources work as constraint, especially for multi-product manufacturing facilities. For instance, shared resources between electronic/optical/telephonic products.
- Batch prioritization especially for mixed manufacturing (make-to-order (MTO) and make-to-stock (MTS)) environment to fulfill customer requirements.
- Preventive maintenance and unexpected machine failures.
- Additional complexity added due to the resource unavailability, production delays, due dates and material constraints.

3. BPM Solution Expectations

The operational control parameters identified in previous section poses significant pressure on manufacturers to deliver orders on time efficiently. This raises other issues such as high WIP, low process performance, increased setup times, decreased throughput, etc. In order to deal with manufacturing system complexity and the problems, there is the need to develop advanced solutions [13 and 24]. Data was collected from the industrial partners and consultants; the solution requirements for such system can be given as;

- Overall production and bottleneck process visibility instead of driving the production process based on bottleneck only. Modelling and What-If can improve the decision making process by providing the quantitative information with respect to different schedules. Dynamic modeling can assist to characterize the process activities and decision points.
- What-If analysis through scenario simulation in order to achieve smart scheduling based on the selected KPIs. Especially for multi-objective problems, for instance, in a mixed MTO and MTS environment manufactures wants to increase the throughput, offer reliable due dates and decease the WIP.
- Reactive scheduling to mitigate the unexpected events such as raw material shortage and machine breakdowns. Simulation tool can provide quick solution to such problems, for instance Kang et al. [8], has applied such approach to the semiconductor industry and illustrated how this can deliver benefits to wire and cable industry.
- Forecasting to support the future requirements and strategic planning. For example, resource requirement predictions, planned maintenance, development of new processes, procedures and predicting their effect on the whole system.
- Management and optimization functionality such as buffers, job sequence, batch size, etc.

7. Conclusions

The quest for internal efficiency and external effectiveness mandates that companies have to align their internal settings and resources with external requirements/orders. In order to address these issues, paper illustrated a systematic and structured approach to overcome the barriers of simulation based problem solving approaches (illustrated in Section 1). Along this, paper highlights the importance of understanding a business process and improvement initiatives from the system perspective rather than individual process. Therefore, from the business process modeling and optimization aspect there are four major components needs to be considered;

- Environment; the most important feature of a system, as it defines the framework within which a system of organized activity operates. This included, men, machine, material supplier, competitor, customer, etc. Carbon fiber manufacturing process case study includes mainly men, machine and material in the form of modeling the problem, but the selected KPIs were relating it to the overall organizational objectives mainly derived from customer expectations.
- Decision maker; the whole idea of the proposed methodology is assisting decision making to make more informed decisions. Therefore, an iterative approach was used during the DES model development to make sure that system represents the real world problem.
- Objectives; it is important that objectives should be defined by taking into account system as whole. Otherwise, process improvement activities may not deliver the organizational wide benefits. In order to avoid the mistake of considering the objectives which are related to some activities than entire system, KPIs for problem under investigation were associated with overall organization objectives i.e. throughput, resource utilization and cost.
- Alternative solutions; combining the DoE approach with DES enabled the What-If analysis. This has helped with both understanding the system dynamics and operations optimization according to the given set of constraints.

The second aspect of the paper is to relate the proposed method with the wire and cable industry. The proposed approach can be applied to any manufacturing and service sector for problem solving, process improvement, optimization and decision support as long as the system under study can be modeled and constraints are identified in the form of controllable and uncontrollable operational parameters. Therefore, based on above argument Section 6, illustrates a generic manufacturing process and operational control parameters for wire and cable industry. This extends on the author's previous work in the area of autonomous scheduling to improve the scheduling process using evolutionary algorithms [8].

This paper looks at the process improvement and optimization issues from a wider perspective rather than relating to a problem. For instance, the system can be modeled at higher level, focusing on production process only to add end-to-end throughout the supply chain or to do strategic planning rather than focusing on operational problems i.e.

- Supply chain modeling; the raw material supplier, logistics network, production, distribution centers and customer can be considered as individual business process and the constraints at each level becomes the operations control parameters for these processes.
- Project planning; to understand the project deliver plan using a systematic approach in order to make sure if projects can be delivered at the given level of complexity and uncertainty and what are the resource and budget requirements to deliver such projects. In this can project activities are modeled as

simulation modeling elements and the constraints becomes the operational control parameters [28].

Form the implementation aspect, the proposed approach is validated using the Simul8 and alternative scenarios were derived based on the full factorial approach. However, there are other tools which can be used according to the solution requirements, such as Preactor APS and Simio modeling tool. Therefore, from modeling aspect, it is planned that proposed method to be validated using these tools in order to identify the best tool based on different cases. The other aspect of future work includes, process improvement and optimization using the autonomous and evolutionary algorithms. This can provide a range of algorithm to choose from based on the computation cost and time, quality of solution and problem complexity.

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10. Pictures of Authors

Dr Parminder Singh Kang is working as a Research Fellow at De Montfort University (DMU), Leicester, UK. He received B-Tech degree (Computer Science and Engineering) in 2006 form Punjab Technical University, India. He received M.Sc. degree (IT) in 2008 and completed his PhD (Improving Manufacturing Systems Using Integrated Discrete Event Simulation and Evolutionary Algorithms) in Manufacturing Science in 2012 at DMU, UK. He is member of institution of mechanical engineers (IMechE), Institution of Engineering and Technology (IET) and The American Society of Mechanical Engineers (ASME). He has over 6 years of experience working on externally funded collaborative industrial R&D cross-disciplinary project in the area of organizational operations optimization. His research interests are; evolutionary algorithms, combinatorial optimization, simulation modeling, Lean/Six Sigma and application of these techniques (integrated approaches) in industrial/service process improvement and operations optimization.

Adam Aboutaleb is a Research Fellow and a PhD student at the Advanced Manufacturing Processes and Mechatronics Centre of De Montfort University, Leicester, UK. Adam completed his MSc degree in Mechatronics at De Montfort University with distinction in 2012. He joined the Advanced Manufacturing Processes and Mechatronics Centre in 2012 and has been involved in the management, supervision and implementation of several Innovate UK funded projects. The projects integrate different engineering disciplines such as manufacturing, material science, information technology, art and media, civil and mechanical engineering. His research targets the evaluative modelling and autonomous control of production lines. He also has 4-year industrial experience in equipment maintenance and project planning and coordination for multi-million dollar projects in container terminals.

Christopher Ugo Silva has 9 years experience in technical textile industry, 3 years experience in testing thermoplastics and he is incharge of composite testing and sample manufacturing for 5years.

Alexander Erhart is a founding partner of NEO Industrial Engineering. It has 10 years of experience in production management and Advanced Planning and Scheduling systems and is responsible for several projects and cases recognized and awarded internationally. Is dedicated to research high-level technological solutions for production management and to find ways to adapt them with a touch of creativity to the reality of their customers. Industrial Engineering from UFRGS with MBA in Business Logistics by FVG and PMP certification by PMI.

Victor Todeschini is a business consultant of NEO Industrial Engineering; specialize in Advanced Planning and Scheduling systems. With formation in Industrial Engineering from UFRGS, he has over 2 years of experience working along with best in class companies in implementation of Advanced Planning and Scheduling solutions. His main research interests are new technological concepts connecting along with software such as Preactor, focusing on bringing new features and insights to the customers.

Alistair Duffy is Professor of Electromagnetics at De Montfort University (DMU), Leicester, UK. He received his BEng (Hons) and MEng degrees in 1988 and 1989, respectively, from University College, Cardiff, Wales. He read for his PhD with professors Christopoulos and Benson at Nottingham University, graduating in 1993. He also holds an MBA from the Open University, UK, graduating in 2004. He is a Fellow of the Institution of Engineering and Technology (IET, formerly the IEE) and a Senior Member of the IEEE since 2004. He has published approximately 200 papers, mostly on his research interests of validation of computational electromagnetics; physical layer components, particularly communications cabling, and electromagnetic compatibility testing and technology management.