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Manufacturing Systems Management and Automation

6-1

Development of a robust handling model for foundry automation

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Abstract. This paper compares the simulation and experimental results for robust part handling by radially symmetric cylindrical electromagnetic gripper heads, that are used in foundry manufacturing assembly operation. Knowledge of the direct holding force is essential to determine if a given electromagnet is capable of preventing part slipping during pick and place operation. Energy based model and the magnetic circuit model have been described. The latter is developed further and compared with results from a FEA software. It was found that the magnetic circuit model, although simple in form, was limited in its ability to accurately predict the holding force over the entire range of conditions investigated. The shortcomings in the model were attributed to its inability to accurately model the leakage flux and non-uniform distribution of the magnetic flux. A finite element allowed for the ability to couple the mechanical and magnetic models. The finite element model was used to predict the magnetic field based off the solutions to the mechanical (σ) and the magnetic model (B).

Keywords: Handling Electromagent Design, Foundry Automation

1. Introduction

The Robot grippers are used to position and retain parts in an automated assembly operation. Electromagnet grippers offer simple compact construction with no moving parts, uncomplicated energy supply, flexibility in holding complex parts and reduced number of set-ups, and are thus suitable to ferrous metalcasted parts. However, their use is limited to ferrous materials (Iron, Nickel, Cobalt), electromagnet size is directly dependant on required prehension force; residual magnetism in the part when handled when using DC supplies requires the additional of a demagnetizing operation to the manufacturing process. Smart materials, commonly classified according to their energy transduction mode as piezo-electrics, shape memory alloys, and magnetostrictives, have been shown to be useful in low bandwidth application, and micro gripping applications, but they still have limitations in a high volume manufacturing environment [1]. While the choice of material limits application, and demagnetizing is a requirement, the holding force is an important unknown.

An electromagnet consists of at least one pair of north and south magnetic poles that are separated by an airgap. In this way, there is practically no magnetic field present when a current flows through the coil, because air presents a very high reluctance to the magnetic flux. When a part is placed on the surface of the electromagnet in such a way that it connects a north and south pole, the magnetic flux can be established, given that the part is made of a ferromagnetic material. The magnetic flux will produce a force of attraction between the part and the electromagent, as mentioned in the previous section. Two parts made of the same material and having the same geometry and dimensions could experience a different force of attraction on a given electromagnet if the contact conditions between the workpiece and the electromagnet are different for the two of them. Of one of the parts has a rougher surface or has a larger flatness error, the contact interface will have larger airgaps that have to be transversed by the magnetic flux in order to complete the magnetic circuit.

The users of electromagnets in iron foundries know that factors such as material hardness, surface contact conditions, and electromagnet design influence the holding force. Most of the available literature in foundry automation is of a commercial nature [2,3,4]. The author believes that a predictive model for determining the holding force will enable the design of the optimum operating geometry and/or conditions to prevent part slip during robot handling/assembly. Consequently, the need for costly and time intensive experimentation will be minimized.

This paper compares the results from the magnetic circuit model and energy model with available commercial software COMSOL, for a cylindrical radially symmetrical electromagnet head, and substantiates it with experimental analysis.

2. Modeling electromagnetic behaviour

Several energy based models have been created in an attmept to capture the non-linear behaviour or

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electromagents. Modeling techniques bu Dapino et al [5] include a thermodynamic approach for estimating magnetization to field. Additional modeling techniques have been reported by Sablik and Jiles [6], where internal energy minimization is used to ensure mechanical equilibrium. Analytical methods have also been depevloped, but mainly for predicting magnetostrictive performance [7]. When analyzing complex geometries finite element method generally gives more accurate results.

In the following sections, the energy based model, magnetic circuit model and the FEA model used to simulate experimental data are explained. As a basis for comparison, the analytical method for calculating magnetization factor for cylindrical electromagnets is compared to FEA predictions where the effect of airgaps and varying current through the electromagnet coil on the holding force is investigated. Comsol Multiphysics 4.0 magentostatics (with currents) is the finite element model was used in the research.

To determine the magentization effect via FEA approach the external field is calculated by determining the magnetic field at a point of interest in space at a certain distance from the magnet, in the absence of the sample part. The magnetization factor was calculated for several aspect ratios, where the thickness of the sample always remained 2-inches. The airgap was varied to change the aspect ratio, and the effect of electromagnet coild heating over a period of time was observed.

3. Industrial setup

The six axis ABB ERB 6400 robot used in foundry assembly operation is shown in Fig. 1. A Sony XCG-U100E overhead camera was used for identifying the orientation of the part lying on the conveyor belt, which was internally tracked by the robot. The image captured by the camera was processed by Scorpio Vision System (Tordivel AS) and transferred via closed network Ethernet connection to the Robot. The robot gripper then moved the electromagnets accordingly to pick the part.

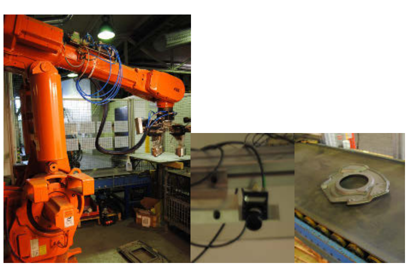

Fig. 1. Robot Assembly Cell.

The purpose of the vision system was to recognize the part and extract the orientation. The second purpose of the vision system was to assist in decision making. The part orientation was identified by the markers (Fig. 2) which were cast in the part. The vision system conveyed the parts orientation to the robot gripper via the Ethernet and the electromagnets were translated to orient towards the grasping the part.

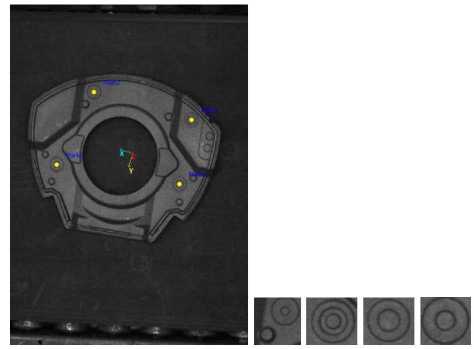

Fig. 2. Markers casted on the part.

4. Magnetic field distributions

This section concentrates on the analysis of different basic electromagnet setups and their effects on the magnetic properties of a system. Magnetic field distributions will be used for each setup to emphasize key differences between different designs.

As a basis for comparison, the analytical method for calculating the magnetization factor of a cylindrical core [34] is compared to FEA predictions,where the effect of aspect ratio on magnetization is investigated. A COMSOL Multiphysics 4.0 magnetostatic (with currents) finite element model was created with a geometry consisting of a rectangular core immersed in a coil, surrounded by an air domain with dimensions of three times the largest dimension of the rod and coil (Fig. 3).

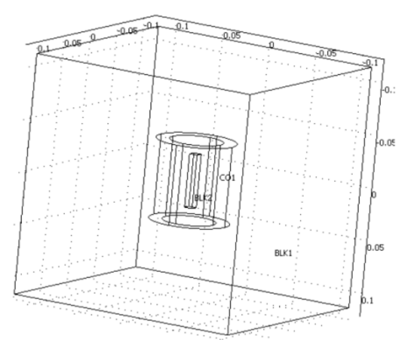

Fig. 3. COMSOL Magentostatics (with currents) geometric rod coil setup.

Equation 1 gives a general expression for determining the effective magnetic field within a sample, with a known value of N_d (magnetization factor) [8]. Since calculation of the effective magnetic field (H_{eff}) requires a knowledge of N_d (geometry dependent), the magnetic field within the sample is normally difficult to calculate (especially for complicated geometries).

$$H_{eff} = H_{ext} - H_d = H_{ext} - N_d M \quad (1)$$

Ellipsoidal geometries have been shown to have a relatively constant magnetic field distribution, leading to one value of magnetization factor for the entire geometry. An analytical expression for calculating the demagnetization factor as a function of a dimensional ratio (k) was developed by [9] (Equation 2). The dimensional ratio, k, is determined by dividing the length of the semimajor axis by the semiminor axis.

$$N_d = \frac{1}{k^2 - 1}\left[\frac{k}{\sqrt{k^2-1}}\log_e\left(k + \sqrt{k^2-1} - 1\right)\right] \quad (2)$$

It was desired to simulate the magnetic field behavior along the radius and length of the rod. A 2D axisymmetric, magnetostatics (with currents) model was utilized. The rod was placed at the r = 0 location and was surrounded by a coil. The rod and coil setup is surrounded by an air domain (μR = 1) with dimensions that are three times the length of the coil, which is the largest component of the circuit. A current density of 3e6 A/m2 was assigned to the geometry corresponding to the coil. A relative permeability of 50 was assigned to the rod for the experiment.

Figure 4 shows a 2D axisymmetric streamline of the magnetic field when the magnetic sample (μR = 50) is placed inside the coil. It is evident that due to the demagnetization effect, the magnetic field leaks throughout the length of the rod (i.e., some streamlines fail to travel the full distance of the sample). However, if a magnetic circuit is incorporated into the design of the transducer, then the flux leakage can be drastically reduced. In Fig. 5, a steel flux return path is added to the same setup as in Fig. 4, with μR = 2000 for the steel. The use of a well defined magnetic circuit will allow for the full use of the material capabilities, as there is negligible field lost due to flux leakage.

Rods having a radius of 0.25-inches were analyzed for aspect ratios of 1, 2, and 4 (0.5, 1, and 2-inch long rods respectively). The magnetic rod is assumed to have a constant permeability of 50. The steel flux return path discussed in the second case has a permeability of 2000.

The current density used here is 3e6 A/m2 for all cases. First, the magnetic field distribution was studied for the no steel flux return case. The radial magnetic field distribution (at the mid-height of the rod) was studied for the no steel flux return case, for cylindrical rods with aspect ratios of 1, 2, and 4, and all with radii of 0.25-inches. The magnetic field data for each aspect ratio was non-dimensionalized according to its maximum magnetic field value. The radial position was also non-dimensionalized (i.e., max field is one, and outer radius position is one).

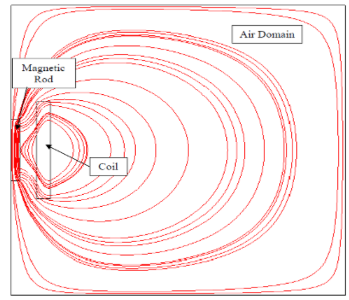

Fig. 4. 2D axisymmetric view of magentic field streamlines showing lines of flux leakage resulting from rod and coil setup.

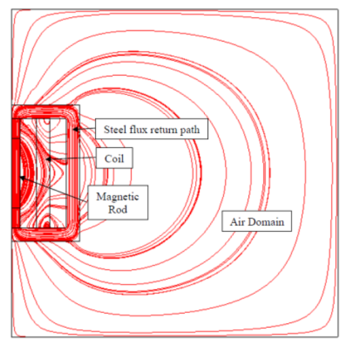

Fig. 5. 2D axisymmetric view of magentic field streamlines showing flux leakage for rod and coil with steel flux return path.

Figure 6 shows the non-dimensional results for the three different aspect ratios. There are two sets of data shown for each aspect ratio. The dashed lines correspond to rods with length and width of half the sample shown by the red lines. Using these dimensions gives the same aspect ratio. It is evident that the non-dimensional magnetic field distribution does not vary for rods of the same aspect ratio. It is important to note that this is only true when comparing magnetic field distributions of the same shape. Also, these distributions are unique to the specific coil design and applied current density. Furthermore, Fig. 6 shows that lower aspect ratio samples experience a larger amount of non-dimensional magnetic field leakage from their centerline to the outer radius. Additionally, it is evident that the magnetic field increases from the center of the rod and reaches a maximum at the end of the rod for all aspect ratio cases. It should also be noted that the relationships shown in Fig. 6 are parabolic. This parabolic magnetic field behavior plays a key role in the element type that is chosen for the mesh.

Next, the magnetic field distribution along the length of the rod was studied for the no steel flux return case, for cylindrical rods with aspect ratios of 1, 2, and 4, and all with radii of 0.25-inches. Again, the magnetic field data for each aspect ratio was non-dimensionalized according to its maximum value. The magnetic field behaviour described in the aboe two cases is summarized in Table 1.

As the aspect ratio is increased, the percentage difference between the maximum and minimum magnetic field through different locations along the radial span decreases. On the contrary, the percentage difference between maximum and minimum magnetic field along the length increases for samples with higher aspect ratio ratios. Differences in magnetic field of 80.9% were seen along the length of a 2-inch, 0.25-inch diameter sample.

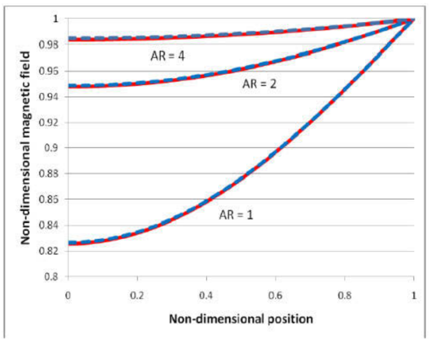

Fig. 6. Nondimensional radial magnetic field verses non dimensional position for a rod and coil setup with varying aspect ratios. The dashed lines show rods with different dimensions that yield the same dimensions as the rods shown in the solid lines. All data is normalized to its respective maximum magnetic field.

Table 1. Percentage difference of magnetic field along radius and length of cylindrical samples with radii of 0.25-inches and lengths of 0.5, 1, and 2-inches (aspect ratio ratios of 1, 2, and 4) for rod and coil setup.

Aspect ratio aspect ratio	% difference in magnetic field along radius	% difference in magnetic field along length
1	17.4	54
2	5.2	70
4	1.6	80.9

The radial magnetic field distribution (at the mid-height of the rod) was studied for the steel flux return case, for the same cases as done for the no steel flux return path studies. It was clear that the presence of the steel flux return path increases the magnetic field within the sample, as well as creates a more uniform distribution of magnetic field. Table 2 summarizes the magnetic field behavior. It can be observed that as the aspect ratio increases, the percentage difference between the maximum and minimum magnetic field through the radial span decreases. In contrast, the percentage difference between maximum and minimum magnetic field along the length increases for samples with higher aspect ratios. Differences in magnetic field of 6.5% were seen along the length of a 2-inch, 0.25-inch diameter sample. However, in comparison to Table 1, the steel flux return path eliminates a large amount of the flux leakage leading to small percentage differences in magnetic field along the radius and length of the sample.

It was clear that the spatial variation of magnetic field varies greatly with the setup. The above parametric study suggested that it is important to include a flux return path. It was also found that it is desirable to use samples of lower aspect ratio, as the percentage change in magnetic field is much smaller for lower aspect ratio samples. Seeing these, the magnetic circuit was modeled before experimentation.

Table 2. Percentage difference of magnetic field along radius and length of cylindrical samples with radii of 0.25-inches and lengths of 0.5, 1, and 2-inches (aspect ratios of 1, 2, and 4) for rod, coil, and steel flux return path..

aspect ratio	% difference in magnetic field along radius	% difference in magnetic field along length
1	0.9	0.7
2	0.6	3
4	0.2	6.5

5. Magnetic Models

Energy Based Model

In the magnetic field, the energy associated with the system is distributed throughout the space occupied by the field. Assuming no losses, the energy stored in the system per unit volume when increasing the flux density from zero to B is:

$$W_f = \int_0^B H dB \tag{3}$$

From this expression, a relation for the mechanical force can be obtained by the method of energy or coenergy. These two methods are derived from the principle of conservation of energy and are very well documented in the literature such as Sen 1989, Fitzgerald 1985. The expression for the force obtained with the energy method is:

$$F = -\frac{\delta W_m}{\delta x}\bigg|_{\lambda = constant} = \frac{B^2.A}{\mu_0} \tag{4}$$

Where, λ is the flux linkage, which is equal to the magnetic flux (ϕ) in the system times the number of turns in the coil (N) generating the magnetic field. It can be seen from Eq. (4) that the stored energy in the magnetic field, and thus the mechanical force, is a function of the magnetic flux (or flux density) present in the system. Thus, the available force for a specific device with a given MMF is determined by the reluctance of the device.

Magnetic Circuit Model

The magnetic circuit approach is an analytical method, analogous to electric circuit analysis, for modeling electromagnetic devices [10,11]. Cherry et al. in a classic paper [12], demonstrated the duality between electric and magnetic circuits. The driving force in a magnetic circuit is the magnetomotive force (MMF) $\Im$ which produces a magnetic flux against a coil reluctance $\Re$. The reluctance is defined as:

$$\Re = \frac{l}{\mu A} \tag{5}$$

Where l is the length of the magnetic flux path, A is the cross section area perpendicular to the flux, and μ is the permeability of the material [10].

For a given MMF and $\Re$, the flux ϕ in the circuit can be found from Kirchoff's law for magnetic circuits. The holding force can be computer using the following simple relation:

$$F = \frac{B^2 A}{2\mu_0} \tag{6}$$

Where B represents the magnetic flux density in the airgap separating the components, A is the cross section area of the airgap and μ_0 is the permeability of air.

The flux depends on the overall reluctance of the system. The reluctance is low when there is perfect contact between the part and electromagnet. However, part form errors, e.g., roughness, and deviation from flatness give rise to air gaps between the part and gripper. Since actual size and distribution of the airgaps in the gripper-part interface are difficult to determine for a gripper directly in contact with the part surface; it is proposed to model a small uniform air gap that can be reproduced in an experiment. When the part rests directly on the magnet gripper surface, a uniform air gap equal to the part out-of-flatness error is could be used. It can be assumed here that the reluctance of this air gap is equivalent to the reluctance of the actual contact.

The reluctances proposed in this model include those of the electromagnet, air gaps, part, and the surrounding air medium. The procedure for modeling the reluctances is described next.

Electromagnet Reluctance $\Re_{Electromagnet}$. To simplify the shape path of the flux lines only half of a cylindrical electromagnet is considered.

Part Reluctance $\Re_{Part}$. The part reluctance is calculated using the following equation [7]:

$$\Re_{Part} = \oint \frac{dl}{\mu(l).A(l)} \tag{7}$$

To evaluate this line integral, a numerical integration scheme can be used. The mean path is such that it is normal to the radial line representing the cross sectional area. The variation in part permeability along the flux path is explicitly accounted for in the calculation of the circuit reluctance.

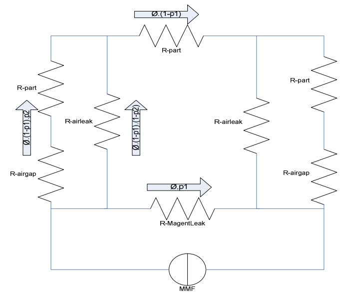

Fig. 7. Equivalent Magnetic Circuit of the Magnet-Part System

Airgap Reluctance $\Re_{Airgap}$. The airgap term applies to the flux lines crossing the magnet-part interface. In reality, the airgap length varies at each point in the interface because of surface roughness and form errors. In this model, an equivalent uniform airgap length is used. The cross-sectional area of the air gap is equal to the magnet-part contact area.

Of the simplifications made above, the use of a mean magnetic flux path is most significant since it implies that the magnetic circuit model cannot predict the distribution of flux in the magnet-part system. However, it can still be used to estimate the total normal holding force and to gain an insight into the effects of magnet and part variables.

Model Solution. Solution of the magnetic circuit model involves determining the flux flowing through each component of the circuit. This is done using Kirchoff's law for magnetic circuits, which states that the sum of MMF in any closed loop must be equal to zero [15]:

$$\sum_i MMF = \Im - \sum_i R_i \phi_i = \Im - \sum_i H_i l_i = 0 \tag{8}$$

where index i represents the i th element of the closed loop. H_i is the magnetic field in the i th element, and l_i is the length of the flux path in the i th element. For the magnet used in the gripper, the equation reduces to:

$$\Im + H_{Work} l_{Work} + (2B_{Airgap} / \mu_0) l_{Airgap} = 0 \tag{9}$$

The factor of 2 in the last term accounts for the crossing of airgap twice, once from the N pole to the part and again from the part to the S pole. For the circuit shown in Fig. 8, the part holding force is produced by the fraction of flux that crosses the magnet-part air gap, which is given by:

$$\phi_P = \phi.(1 - p_1).p_2 \tag{10}$$

where p_1 is the fraction of ϕ leaking and p_2 is the fraction of $\phi.(1-p_1)$ entering the airgap and the part. Equation (10) when combined with Equation (4) gives the mechanical force acting on ½ of the model of the part. The results from the above magnetic circuit model were compared with COMSOL FEA model.

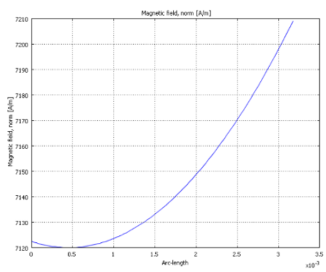

Fig. 8. Field distribution along radius with 6-node element coarse mesh.

COMSOL FEA Model

The magnetic model was created using a 2D axisymmetric magnetostatics (with currents) module, as shown in Fig. 9. The air domain was assigned the dimensions of width and length equal to three times the maximum dimension of the electromagnet. The air and aluminum parts were assigned a µR = 1, steel casing a µR = 2000, and the center rod was assigned a variable permeability via µR(B,σ). The magnetic field is assigned via a current density which has units of current per unit area.

An important boundary condition includes axial symmetry and continuity. Axial symmetry is defined for 2D axisymmetric models at r = 0, and assumes a symmetric condition such that the properties of the system do not vary azimuthally. The continuity boundary condition enforces continuity of the tangential components of the magnetic field via: n x (H2 – H1) = 0. This boundary condition is used at the junction of two different subdomains with different magnetic properties.

When modeling a magnetic circuit, it is important to account for the surrounding atmosphere. Generally, this atmosphere is air, with a relative permeability of one. There have been several ways to model the surrounding air in a magnetic circuit. The two most notable techniques are the use of an air domain and infinite elements. Atulasimha et al. [7] describes how to determine the proper dimensions of an air domain. Another method of modeling the surrounding air is by using infinite elements. Infinite elements are assigned to a small subdomain region which defines the outside of the setup. The outer domain containing infinite elements causes the domain to be stretched to infinity. This allows for the flux lines to flow as far as they normally would without constraints. It was desired to compare the two previously described methods of modeling the surrounding air domain. To do this, the rod and coil was implemented with infinite elements and with air domains of different sizes. The results are shown in Fig. 10, where it was found that an air domain with dimensions of three times the largest geometric dimension of the setup gives same results as infinite elements. It was also desired to determine if larger applied current densities lead to the need for a larger air domain. In Fig. 11, magnetic fields of ~7-7.2 kA/m are seen and the previously specified dimensions of the air domain still give a very good answer as compared to the infinite element result. Fig. 11 shows the same plot as Fig. 10, but at a higher applied magnetic field (~117-120 kA/m). Air domain sizing of three times the largest dimension in each direction still provides an accurate answer.

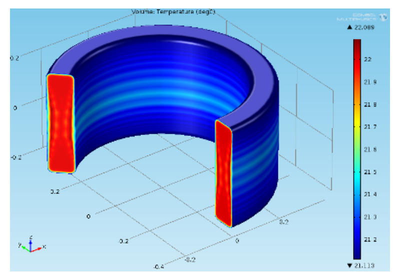

Fig. 9. COMSOL model of radially symmetric electromagnet.

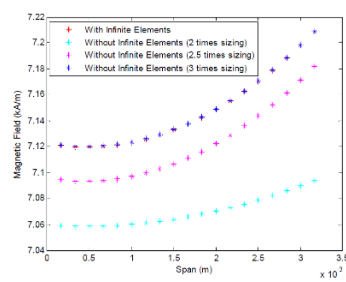

Fig. 10. Radial distribution of magnetic field for rod and coil setup with air domain of different dimensions and infinite elements.

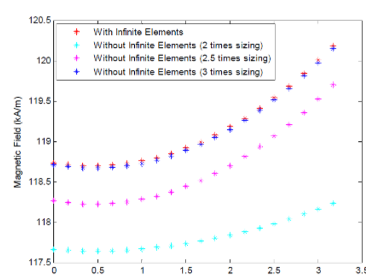

Fig. 11. Radial distribution of magnetic field for rod and coil setup with air domain of different dimensions and infinite elements at high applied magnetic fields.

6. Conclusions and future work

It was shown that a steel flux return path greatly reduces the radial and longitudinal variations of field. The use of infinite elements will generally reduce the total number of elements required in a magnetic model. Seeing this, models using infinite elements will generally prove to be more computationally efficient than using an air domain.

However, infinite elements take longer to solve than standard elements, so there is a tradeoff between using the two methods.The part texture attributes (surface roughness and texture) affect the holding forces of an electromagnet gripper. Future effort in this area will present the effect of these attributes on normal and tangential holding forces.

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Concise process improvement - A process variation diagnosis tool

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This paper is dedicated to the memory of Prof. Valentin Vitanov.

Abstract. This paper examines the efficiency and objectivity of current Six Sigma practices when at the Measure/Analyse phase of the DMAIC process improvement cycle. A method, known as the Process Variation Diagnosis Tool (PROVADT), is introduced to demonstrate how tools from other quality disciplines can be used within the Six Sigma framework to strengthen the overall approach by means of improved objectivity and efficient selection of samples. From a structured sample of products, PROVADT is able to apply a Gage R&R and Provisional Process Capability study fulfilling pre-requisites of the Measure and early Analyse phases of the DMAIC process improvement cycle. From the same samples a Shainin Multi-Vari study and Isoplot can be obtained in order to further the analysis without additional samples. The latter quality techniques are associated with the "Clue Generation" phase of the Shainin System. The PROVADT method is tested in industry case studies to demonstrate its effectiveness of driving forward a process improvement initiative with a relatively small number of samples, which is particularly important for low volume high value manufacturing. Case studies were conducted at a leading manufacturer of microprocessor based electric motor control systems, a global technology, manufacturing and service company that provide advanced systems in the automotive industry and a furniture manufacturer. Using PROVADT and sample sizes of 20 units it was possible in all cases to validate the measurement system and gain an early objective insight into potential root causes of variation, leading to significant cost savings for both companies.

Keywords: Quality management and control, six sigma, electric motors, automotive components, furniture manufacturing.

1. Introduction

A Six Sigma quality improvement project typically follows the five phase improvement cycle: Define, Measure, Analyse, Improve and Control (DMAIC) [1,2]. Six Sigma texts, [1,2], outline many techniques and tools that can be used at each stage of the quality improvement cycle. When it comes to the Analyse phase it often jumps from extremely subjective approach, using brainstorming and cause-and-effect diagrams to form casual hypothesis, to complex statistical tools to validate casual hypothesis. This paper will introduce techniques to improve the weakness in Six Sigma's "exploration" [3].

It is particularly important when the sampling cost is high or low volume of product is available to test. Thus extremely complex Designs of Experiments (DOE) can be impractical and using less powerful screening techniques, like Fractional Factorials, will reduce the numbers of experiments needed but at the expense of higher order interaction effects. Other approaches to identify important factors such as scatter plots can lead to potentially erroneous results as correlations appear by coincidence or are linked by a related underlying cause [2] and cause-and-effect matrices can be extremely subjective. Importantly the real root cause of a quality problem could be missed if DOE is applied based on casual hypothesis techniques to identify root causes.

This paper outlines a sampling strategy known as the Process Variation Diagnosis Tool (PROVADT). The PROVADT was devised to improve the objectivity of the early analysis of a quality problem when there are a large number of factors in a process to analyse and a relatively low volume of product to sample. It can provide a Gage Repeatability & Reproducibility (GRR) study and a Process Capability study, techniques classically used in the Six Sigma Measure and Analyse phase respectively. These techniques take time to apply, and will shine little light on the root cause of a problem.

The PVDT from the same samples allow a GRR and a Provisional Process Capability (PPC) study to be extrapolated, as well as provide a Shainin Multi-Vari (SMV) study and an Isoplot^{SM}, techniques associated with the "Clue Generation" phase of Shainin System [4]. Based on them, the "signature of variation" can be found allowing for a more efficient analysis of a quality problem. The Analyse process starts by reducing down the numbers of factors under consideration, eliminating unimportant factors objectively with data driven information. This reduction in factors with SMV significantly reduces the subjectivity of the early analysis. Thus, later application of DOE is more powerful and more meaningfully used. With fewer important factors to analyse, fewer experiments are needed to fully understand the interaction effects.

2. The PROVADT procedure

The PROVADT sampling structure must be defined before implementation to ensure enough data is collected to fulfil the statistical techniques requirements.

A sample size, n, must be selected, with a minimum of 20 units, as this is the minimum number of units needed to calculate a PPC. This sample size depends also on the data collection time period α and the number β of consecutive units sampled from each batch or time period according to (1).

$$n - \alpha\beta \tag{1}$$

The value for α in a SMV is 3-5 periods, where a sample period could be over a shift, a day, a week if collecting from a flow line or if there is batch production, the periods could correspond to batches. These must be spread out over a time frame in order to capture at least 80% of historical variation. β must be a least 3 consecutive units for a SMV [5]. However n should be greater than 20 to fit the requirements of the PPC, therefore if α=5, β must be 4 or more.

The critical-to-quality characteristic on the samples should be measured repeatedly by a minimum of two appraisers. Let r_i is the number of repeats taken by an individual appraiser, then the total number of measurements taken, r_{Total}, is;

$$r_{total} = \sum r_i \tag{2}$$

The total number of measurements made, φ, is;

$$\varphi = n r_{total} \tag{3}$$

The value of φ is important for the GRR calculation to be valid and is typically 60 measurements or greater. The first n / 2 sampled units are measured by appraiser 1 first then by appraiser 2. The second half is measured by appraiser 2 first then by appraiser 1 and the results can be analysed using GRR, Isoplot^{SM}, PPC and SMV.

3. Case Studies of the Practical Implementation of the PROVADT

3.1. Overview

This section explains two case study implementions of PROVADT. Each case has collected information to both validate the measurement system and gain insight into the potential root causes of the quality problems.

3.2. Case One: Edge Banding Trimming

3.2.1. The Quality Problem

Conducted at a leading furniture manufacturer, the most critical quality issue was an Edge Banding process. This process takes Medium Density Fibreboards, which are cut to the correct width; edge banding veneers are glued and

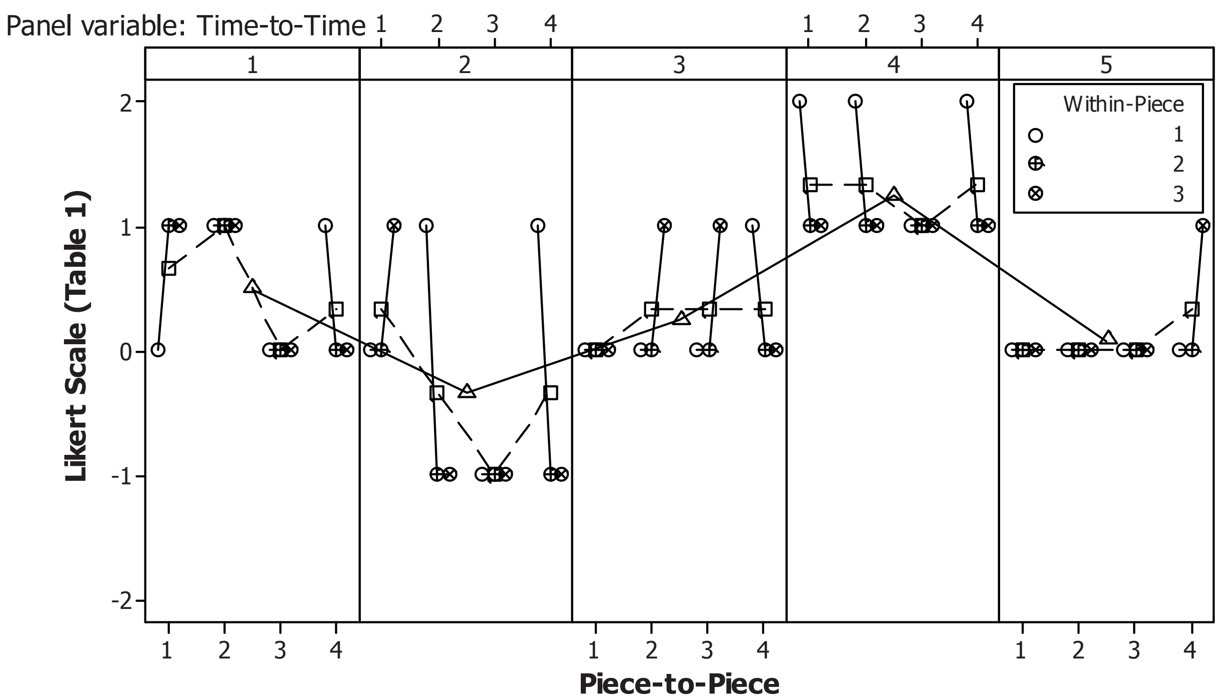

Fig. 1. Shainin Multi-Vari study for Edge 1, showing Red X as within-piece and a possible Pink X Time-to-Time

applied to the freshly cut edges. The boards are then rotated to be cut to the correct length. The final edge banding veneers are then glued and applied to these edges.

All four edges are processed in one run. Output from this process is around 10,000 panels per day and had been subject of a number of quality improvement programmes over many years. At the start of the study the company was seeing around 20% of its output being returned due to edging problems.

3.2.2 PROVADT Implementation

The focus of the process improvement programme was the over- and under- trimming of the edging. In order to use PROVADT, four consecutive panels were acquired from five different time periods, the time periods were selected based on historical data in order to capture 80% of the process variation; each edge was measured three times. This means from a sample of 20 panels (4 panels × 5 time periods), each edge has a total of 60 measurements taken (20 panels × 3 repeated measures). Therefore, the PROVADT parameters: α=5, β=4, n=20, r_{total}=3, r_1=2, r_2=1 and φ=60 are applied. Each of the four edges had the diagnostic tool applied separately as they were trimmed at different points in the machine process. Altough the PROVADT was applied on all edges only the results for edge 1 will be presented, however these results were typical of the four edges.

A quantitative grading score for the problem was introduced. Previously the product was considered as conforming or non-conforming. The modified labelling system, a variant of a five point Likert scale [5], is shown in Table 1. This modification allows the improved expression of the process capability.

Table 1. Modified Labelling System Implemented

2	Reject	(very under trimmed, out of specification)
1	Accept	(under trimmed, within specification)
0	Good	
-1	Accept	(over trimmed, within specification)
-2	Reject	(very over trimmed, out of specification)

3.2.3 Six Sigma Metrics

The results of the GRR experiment, demonstrated there was serious problem with either the measurement system or non-uniformity along the edging. Panel edge 1 had scores of 78%. With a result above 30% classed as inadequate [6].

The PPC of the edge banding process on panel edge 1 is P_p=0.61. The capability study of $P_p \leq 1$ shows extremely low values' indicating the process is failing to produce sufficient products within specification. This is consistent with the high numbers of product returns that were experienced prior to the investigation.

3.2.4 Shainin Multi-Vari Study

A SMV was extrapolated from the PROVADT data. The SMV Study for edge 1, fig. 1, is typical for the four edges. The largest signature of variation or Red X, is a within-piece problem. The within-piece variations are the groups of 3 circles joined by a solid line. This is a typical pattern when there is a measurement system problem or non-uniformity along the edge [5].

The overall SMV investigation clearly showed the Red X was predominantly a within piece problem. This was consistent with the GRR study which highlighted large variation across measures of the same piece. Although the SMV showed there was piece-to-piece and time-to-time variation, it determined that the factors responsible for the within-piece variation had the biggest effect on improving the capability of this process.

3.2.5 Conclusions of the Edge Banding Case Study

From PROVADT the following previously suspected factors were ruled out of the investigation:

- Different size panels were affecting trimming performance; if the edging and trimming machines were affected by the size of the panels there would have to be a significant batch to batch change in variation.
- Settings are being altered between batches; again the effect of changing setting to accommodate different size panels would show up as a batch-to-batch problem.

From the application of PROVADT future investigations should be focused on:

- Full validation of the measuring system using Isoplots to ensure large variation due to a poor measurement system isn't masking another problem.
- If the measurement system is found to be accurate, the investigation should focus on the edging and trimming machines, as the Red X variation results from non-uniformity along the edging.

These follow-up investigations were conducted in-house and the Quality Engineer commented that the project team had *"driven the project further in 2 weeks than it had been in the previous 2 years"*.

3.3. Laser weld mechanical strength

3.3.1 The Quality Problem

Conducted at a global manufacturing company providing advanced systems to the automotive industry, the process scrutinised involved an automated laser welding process used to weld Field-Effect Transistors (FET) to a stamping grid. This component is then used as part of a power steering module. There was concerns over the consistency of the current online destructive shear test method for mechanical strength. A non-destructive peel test was developed in order to establish a statistically valid measurement system. The peel test involves applying a 5N point load on the FET and measuring the deflection.

3.3.2 PROVADT Implementation

In order to validate the experimental non-destructive peel test a PROVADT analysis was planned. The only variation from the previously outline strategy was to collect 24 samples rather than 20. Therefore the PROVADT parameters: α=6, β=4, n=24, r_{total}=3, r_1=2, r_2=1 and φ=72 are applied. This decision was made to evenly sample across the entire shift. Samples were collected to ensure 80% coverage of the historical process variation. In order to asses reproduceability the samples were tested twice on a 500N load cell and once on a 5kN load cell. Although each stamping grid contains 4 FETs, only the results for FET 1 are shown, since.they are representative of all 4 FETs.

3.3.3 Isoplot^{SM} Interperatation

The Isoplot result in Fig. 2 from testing the FETs demonstrate that the variation present due to the measurement equipment is large compared to the variation present due to the product.

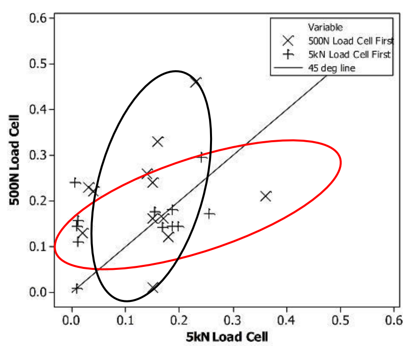

Fig. 2. Isoplot^{SM} result for FET 1 demonstrating the test effecting the characteristic of the weld

It also demonstrates the results form two distinct groups, shown in red and black, splitting samples tested on the 500N Load cell first from those tested on the 5kN load cell. This is a clear indication that the peel test is effecting the characteristic of the weld and is therefore destructive, counter to the previous belief that it was non-destructive.

3.3.4 Shainin Multi-Vari Study

The SMV study in fig. 3 demonstrates that the with-in piece variation is the Red X. This is consistent with the Isoplot in fig. 2 which demonstrates that there is a large amount of measurement variation.

3.3.5 Conclusionsof the Laser Weld Case Study

GRR was not performed. The graphical Isoplot^{SM} demonstrated the test was destructive. Thus the common assumption made in GRR calculations that the sample is robust against the measurement process is not valid.

As a result the experimental Peel Test was scrapped and the in-house team estimated a £10,000 saving in labour and resources compared to the classic validation investigations.

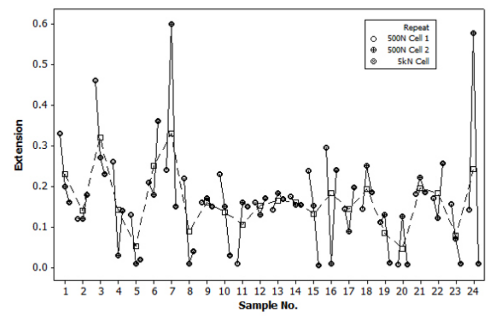

Fig. 3. Shainin Multi-Vari Study for FET 1 showing large with-in piece variation

4. Conclusions

This paper has presented a method for increasing the efficiency and subjectivity of diagnosing a process problem. PROVADT builds on the established methodology and methods of Six Sigma's DMAIC process improvement cycle. Parameters are set out which can capture a GRR study and a PPC Study necessary in the Measure and early Analyse phases of the DMAIC cycle. The parameters also allow for a SMV study and Isoplot^{SM} to be collected from the same sample. These graphical tools come from the Shainin System, but when applied in the context of PROVADT they can add subjective analysis by narrowing down the root causes of quality problems within a Six Sigma framework. Minimum parameters were demonstrated in all case study material. From 20 units it was possible to fulfil the pre-requisites required to perform a GRR, PPC and SMV Study. It was also reported how the PROVADT method on all occasions drove the improvement projects forward from the samples required to validate the measurement system.

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An evaluation of physics engines and their application in haptic virtual assembly environments

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Abstract. Virtual Reality (VR) applications are employed in engineering situation to simulate real and artificial situations where the user can interact with 3D models in real time. Within these applications the virtual environment must emulate real world physics such that the system behaviour and interaction are as natural as possible and to support realistic manufacturing applications. As a consequence of this focus, several simulation engines have been developed for various digital applications, including VR, to compute the physical response and body dynamics of objects. However, the performance of these physics engines within haptic-enabled VR applications varies considerably. In this study two third party physics engines - Bullet and PhysX^{tm}- are evaluated to establish their appropriateness for haptic virtual assembly applications. With this objective in mind five assembly tasks were created with increasing assembly and geometry complexity. Each of these was carried out using the two different physics engines which had been implemented in a haptic-enabled virtual assembly platform specifically developed for this purpose. Several physics-performance parameters were also defined to aid the comparison. This approach and the subsequent results successfully demonstrated the key strengths, limitations, and weaknesses of the physics engines in haptic virtual assembly environments.

Keywords: virtual reality (VR); physics engine; Bullet; PhysX; haptics; haptic assembly; virtual assembly.

1. Introduction

Physical based modelling (PBM) uses physics simulation engines to provide dynamic behaviour and collision detection to virtual objects in virtual environments emulating the real world. This results in better appreciation and understanding of part functionality and can also lead to improved training of manual tasks [1,2]. However, there are several challenges when haptics is integrated with physics engines, e.g. synchronization, non-effective collision detection, high computational cost and a negative impact on the performance of the application [3]. This is due to the fact that simulation engines are not adapted to haptic rendering, mainly because the typical frequency of haptics simulations is over 1 kHz and around 100 Hz for physics simulations [4,5].

This work presents an evaluation of two physics engines for haptic environments to assess their performance in haptic assembly tasks. The experiments are aimed to identify the strengths and weaknesses of each simulation engine.

2. Related work

Physics simulation engines have been used in many applications from computer games through to movies. Laurell [6] identified five key points in any physics engine: contact detection, contact resolution, force calculation, integrating motion and the impact of real time constraints (time step) where anything below 25 frames per second (fps) is perceived as slow and stammering. Additionally, the update rate of the whole system, both graphics and physics, must be less than 40 milliseconds per cycle.

Howard and Vance [7] found that while mesh to mesh assembly enabled accurate collision detection, realistic physical response was not demonstrated particularly when objects had continuous contact with each other since excessive surface stickiness and model penetration was observed. The physics update rate was found to be directly related to the number of contacts generated between colliding geometries.

Seth, et al. [8] identified three main challenges that virtual assemblies must overcome to increase the level of realism: collision detection, inter-part constraint detection and physics-based modelling.

Seugling and Rölin [3] compared three physics engines - Newton, ODE and PhysX - against the following run-time executions: friction on a sliding plane, gyroscopic forces, restitution, stability and scalability of constraints, accuracy against real, scalability of contacts (pile of boxes), stability of piling (max number of stacked boxes), complex contact primitive-mesh, convex-mesh and mesh-mesh. According to their results PhysX was the best evaluated simulation engine except in the stability of piling test and the mesh-mesh collision detection due to unwanted behaviour.

Boeing and Bräunl [9] carried out an investigation to compare PhysX (formerly Novodex), Bullet, JigLib, Newton, ODE, Tokamak and True Axis using PAL (Physics Abstraction Layer). Their comparison criteria included: integrator performance, material properties, friction, constraint stability, collision system and the stacking test. They concluded that PhysX had the best integrator method whereas Bullet provided the most robust collision system.

On the other hand Coumans and Victor [10] made a simple comparison analysis of the following physics engines: PhysX, Havok, ODE and Bullet. Collision detection and rigid body features were used as the comparison criteria. According to the authors PhysX was the most complete engine.

Glondu et al. [4] introduced the possibilities of implementing a modular haptic display system that relies on physical simulation and haptic rendering. With this in mind, four physical simulation libraries are evaluated: Havok, PhysX, Bullet and OpenTissue. The performance criterion was based on computation time, stability and accuracy. PhysX showed penetration in some of the tests whilst Havok showed the best average computation time, stability and friction accuracy.

The previous background study has revealed that several research works have been conducted to evaluate different simulation engines. In general, it is concluded that PhysX is the most complete simulation engine. However, these works have not considered the use of haptic rendering in the virtual environment being evaluated. Thus, it can be said that the performance evaluation of simulation engines in haptic enabled virtual environments is still needed. Hence, the objective in this work is to conduct a series of experiments to find the most appropriate simulation engine for a specific haptic application. It is envisaged that the work reported in this paper can contribute to the haptic research community.

3. System overview

A haptic assembly virtual platform, named as HAMMS, has been developed and is shown in Fig. 1. The HAMMS system (Fig. 1) comprises the Visualization Toolkit libraries (VTK 5.8.0) and the Open Haptics Toolkit v3.0. Two physics engines i.e., PhysX^{TM} v. 2.8.4 and Bullet v. 2.79, have been integrated and the user can select between the two during run time. Single and dual haptic is provided using Sensable's Omni haptic device. One of the main characteristics of HAMMS is a control panel where the user can modify in real time simulation parameters; haptic properties like stiffnes, damping and friction; and physical properties like mass, restitution, tolerance, etc.

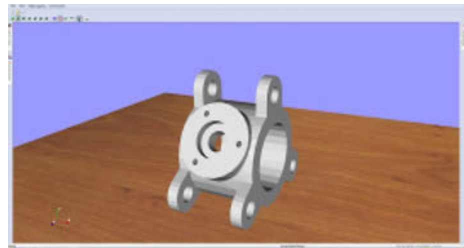


Fig. 1. Virtual haptic assembly application

4. Comparative analysis

In order to identify the usefulness and capability of the two physics engines in haptic virtual assembly environments, a set of virtual assembly tasks were defined and carried out using the two physics engines.

4.1. Model representation

Collision detection is a key aspect of assembly analysis and it is directly related to the model representation in the physic simulation engine [11]. Assembly tasks may comprise several objects or components with different shapes. In general, objects can be divided into two groups: convex and concave objects, being the last the most common objects in assembly tasks.

Bullet 2.79 use GIMPACT libraries to calculate collisions for concave objects represented by a triangular mesh, its representation is very similar to the graphic model as shown in Fig. 2. A convex decomposition algorithm such as HACD [12] can also be used to create concave shapes.

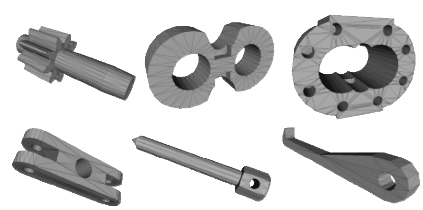


Fig. 2. Physic representation of objects using GIMPACT

PhysX v2.8.4 does not support collision detection for triangular meshes; however, an algorithm to create a concave compound object from a triangle mesh, convexFT (CFT), is provided. The algorithm transforms each triangle of the mesh into a convex element, so the final shape has as many convex hulls as triangles in the original mesh.

4.2. Assembly tasks

Five assembly tasks were selected to analyse the performance of each physics engine in HAMMS:

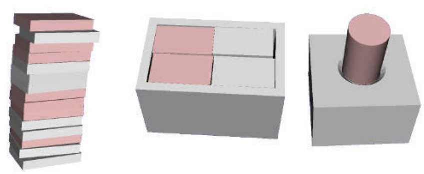
(1) A pile of boxes assembly task was selected to evaluate the manipulation and performance of primitive

shapes, it is also used to analyse the simulation engine performance and stability where multiple and accumulative contacts are considered, Fig. 3 (a).

(2) The packing boxes assembly task, Fig. 3 (b), is useful to identify the physics engine performance using different representation algorithms such as convex decomposition or triangular meshes. The purpose of this task is to observe the collision response and stability when multiple contacts in different directions are present.

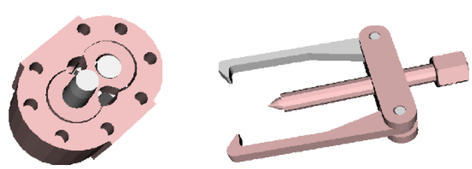
(3) The peg and hole assembly task which is commonly used in assembly tests because it represents a generalized case of cylindrical parts' assembly, Fig. 3 (c).

(4) A more complex pump assembly task, Fig. 4a, and (5) a bearing puller [Fig. 4 (b)] are selected as they represent the virtual models of real components with complex shapes.



(a) (b) (c)

Fig. 3. Assembly tasks: a) Pile of boxes b) Packing box c) Peg & hole



(a) (b)

Fig. 4. Assembly tasks: a) Pump b) Bearing Puller

Each of these five assembly tasks was performed by an experienced user in both haptics and virtual assembly. Five repetitions were carried out for each task, all the tests were performed using a single haptic device to manipulate virtual objects and the mouse to manipulate the camera.

In a physics simulation engine, the integrator method is refered to the numerical methods that it uses for calculate the new position of the object on each time step during the simulation. In order to assess the integrator performance under different conditions, virtual free fall experiments were carried out, measuring the time on reach the floor when the object was dropped from an elevation of 500 units.

5. Results and discussion

The results of the free fall test are shown in Table 1, where it is shown that when the number of triangles of the model is smaller than 300 the integrator performance of PhysX is not affected, whereas in the case of Bullet an increment of 50% was observed. When the object comprises about 2000 triangles the time performance is greatly affected (about 100% increase) for both Bullet and PhysX.

Table 1. Free-falling time with respect to shape (number of triangles)

Shapes	Triangles	Bullet (sec)	PhysX (sec)
Box	12	0.993	2.11
Pin	44	1.011	2.105
Big Cog	276	1.445	2.115
Housing	1934	2.918	4.199

Table 2 shows the influence of the model representation on time performance, these results were obtained with the haptic rendering loop on. The results indicate that when primitive shapes are used in PhysX, free fall time is 5.6 seconds compared to Bullet's 0.9 second average. ConvexFT and convex decomposition (HACD) [12] showed similar results and the best performance for PhysX. Bullet showed a time increment related to the increment of the model shape complexity. Model representation using primitives showed the best performance.

Table 2. Free-falling time with respect to model representation

Model	Representation	Bullet (sec)	PhysX (sec)
Box	Box	0.999	5.627
	Trimesh- ConvexFT	0.993	2.11
Pin	Cylinder	0.998	5.608
	Trimesh- ConvexFT	1.011	2.105
Cog	Trimesh- ConvexFT	1.445	2.115
	Convex dec. HACD	1.428	2.09

Table 3 shows the percentage of increase in time in the free-falling test when the haptic rendering loop was running with respect to a situation where only physics and graphics loops were running, Bullet showed a time increment of 50% when the haptic rendering loop was on and the model was complex, compared to PhysX that showed only an increment of 2%; however, the falling time in all test was smaller using Bullet than using PhysX, this suggest that PhysX rendering loop is more adapted to be used together with haptics. The theoretical falling time is 0.316 seconds.

Table 3. Influence of the haptic loop on free-falling time (%)

Model	Representation	Bullet	PhysX
Box	Box	3.65	0.195
Pin	Cylinder	0.91	0.139
Cog	Trimesh	50.42	2.16
	Convex Dec HACD	48.28	1.08

Table 4 presents the task completion time (TCT) in minutes for each assembly tasks, different model representations and each physics engine. It can be observed that for the assembly tasks of pile of cubes, packing box and peg & hole, when primitives or convex decomposed model representation is used, PhysX posted the least TCT, however when using triangular meshes and Bullet, TCT was least in all the tasks, except the packing box due to unnatural collision response. Real and virtual tests were carried out on the pump assembly. A mean

TCT of 37 seconds was obtained in the real assembly task whilst in the virtual platform the TCT value was 58.3 seconds using Bullet (56% more than the real assembly) and 1.21 minutes using PhysX, this difference may be due to several factors such as the manipulation of virtual models trough the haptic device, physical properties of materials (friction, restitution, mass, etc.).

Table 4. Task completion time

Case	Reps	Bullet (min)	PhysX (min)
Pile of cubes	Primitives	03:59.8	03:24.6
	Convex dec. (HACD)	05:11.8	03:32.6
	Trimesh- ConvexFT	02:41.8	03:23.7
Packing Box	Convex dec. (HACD)	04:17.4	02:09.7
	Trimesh- ConvexFT	03:19.2	02:45.5
Peg & hole	Convex dec. (HACD)	00:13.1	00:07.1
	Trimesh- ConvexFT	00:05.4	00:06.5
Pump	Trimesh- ConvexFT	00:58.3	01:21.0
Puller	Trimesh- ConvexFT	01:33.9	n/a

The results obtained for haptic and physics update rates indicate that PhysX offers better update rates when using non complex geometries represented by primitives or by convex decomposition. However Bullet physics showed better update rates when simulating complex parts represented as triangular meshes.

Assembly performance parameters were evaluated using a scale from 0 to 3, where 0 represents the worst performance and 3 the best. Users assign a value to each parameter according to their perception of the assembly task. Performance parameters include: Collision precision (CP) indicates penetration of virtual models when colliding with other virtual objects. Collision response (CR) is the reaction and how natural objects behave. Assembly stability (AS) indicates if the objects are stable once the assembly is completed. Manipulability (M) indicates how easy the models can be manipulated, and the total (T) indicates the overall score of CP+CR+AS+M. The results are shown in Table 5.

Table 5. Performance evaluation

Case	Model Representation	Bullet					PhysX				
		CP	CR	AS	M	T	CP	CR	AS	M	T
Pile of cubes	Primitives	2	3	2	3	10	3	3	3	3	12
	Convex dec. (HACD)	3	1	1	1	6	3	3	3	3	12
	Trimesh- ConvexFT	3	3	3	3	12	3	3	2	2	10
Packing Box	Convex dec. (HACD)	1	2	1	1	5	3	3	3	3	12
	Trimesh- ConvexFT	3	3	1	3	10	3	2	2	3	10
Peg & hole	Convex dec. (HACD)	2	2	3	2	9	3	3	2	3	11
	Trimesh- ConvexFT	3	3	3	3	12	3	2	3	3	11
Pump	Trimesh- ConvexFT	3	3	2	3	11	3	1	2	2	8
Puller	Trimesh- ConvexFT	3	3	3	3	12	3	2	0	2	7
	Overall	23	23	19	22	87	27	22	20	24	93

It is notable that PhysX displayed better performance than Bullet in simple assembly tasks such as the pile of cubes, packing box and peg and hole. However, in complex assembly tasks like the pump and puller assembly, Bullet showed better performance, less assembly time (58.3 seconds) and better evaluation by the user (11 points of 12 possible) than PhysX (assembly time 1:21.0 min and a total evaluation of 8 points). Moreover, in PhysX the puller assembly tasks could not be completed because the puller screw could not be inserted in the puller base, due to a poor model representation.

6. Conclusions and future work

A performance evaluation of two different physics simulation engines for haptic assembly has been presented. The results have suggested that for assembly tasks that involve non complex geometries like boxes and cylinders (primitives), the use of PhysX offers a better performance than Bullet; however when the assembly comprises more complex shape components, Bullet has better performance than PhysX. A more comprehensive study must be carried out including the effect of simulation parameters, the use of a dual haptics configuration, and others physics simulation engines such as Havok or ODE.

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Effect of weight perception on human performance in a haptic-enabled virtual assembly platform

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Abstract. Virtual assembly platforms (VAPs) provide a means to interrogate product form, fit and function thereby shortening the design cycle time and improving product manufacturability while reducing assembly cost. VAPs lend themselves to training and can be used as offline programmable interfaces for planning and automation. Haptic devices are increasingly being chosen as the mode of interaction for VAPs over conventional glove-based and 3D-mice, the key benefit being the kinaesthetic feedback users receive while performing virtual assembly tasks in 2D/3D space leading to a virtual world closer to the real world. However, the challenge in recent years is to understand and evaluate the added-value of haptics. This paper reports on a haptic enabled VAP with a view to questioning the awareness of the environment and associated assembly tasks. The objective is to evaluate and compare human performance during virtual assembly and real-world assembly, and to identify conditions that may affect the performance of virtual assembly tasks. In particular, the effect of weight perception on virtual assembly tasks is investigated.

Keywords: virtual assembly platforms; haptics; assembly task; weight perception.

1. Introduction

According to Howard and Vance [1], a successful virtual assembly environment requires virtual parts to emulate real parts in real world. Two basic methods for simulating physical part behaviour are physically based modelling (PBM) and constraint based modelling. PBM uses Newtonian physics laws to describe the motion of objects and forces acting on bodies and to model realistic behavior by simulating the effect of gravity and collision response between objects in the virtual environment.

Several VR platforms for mechanical assembly have been developed over the years. From these developments, it has been observed that the time required to complete a virtual assembly task is always larger than the time required for the same assembly task in the real world. Several factors that may contribute to this difference include: the interface used (haptic device, glove, 3D mouse, etc), the manipulability of virtual objects, virtual objects shape and weight, camera manipulation, rendering type (stereo-view, 2D screen, head mounted displays), force feedback, etc.

In this paper the influence of weight of virtual objects in virtual assembly task is investigated in order to identify their effect on the completion time of virtual assembly tasks. The investigation is carried out using a virtual PBM assembly platform enabled with haptics.

2. Related work

During the last decade several researchers have proposed different types of virtual assembly environments with some interesting conclusions. Wang et al. [2] analysed methods of dynamic simulation that may affect the assembly task. A scaling factor for gravity was used, which was attained by trial and error. It was concluded that dynamic simulation of parts in virtual environments greatly enhances the realistic feelings of virtual spaces but does not contribute significantly to the assembly task.

On the other hand, Lim et al. [3, 4] investigated the impact of haptic environment on user efficiency while carrying out assembly tasks. It was observed that small changes in shape, the use of full collision detection and the use of stereo-view, can affect assembly times in haptic virtual assembly environments, Similar results were obtained by Garbaya [5], who observed that human operators have superior performance when provided with the sensation of forces generated by the contact between parts during the assembly process.

Huang [6] studied the effects of haptic feedback on user performance when carrying out a dynamic task using a beam and ball experiments. The results showed that user performance is affected by the magnitude of the force feedback and the complexity of the system dynamics.

The problems related to haptic interaction between human operator and virtual environments were investigated by Tzafestas [7]. The results demonstrated that human perception of weight when manipulating objects in virtual environments is similar to the pereception when manipulating real objects. It was also concluded that imperfections and limitations of the mechatronic haptic feedback device may lead to a small decrement on the user performance.

The influence of control/display ratio (C/D) on weigth perception of virtual objects was evaluated by Dominjon [8]. The results showed that when using a C/D ratio smaller than 1, amplification of user movements on virtual environment, the participants perceived the manipulated object ligther than its actual weight, in some cases it was even possible to reverse weight sensation to make a heavy object feel lighter than a light object. This suggested that mass can be added to the list of haptic properties that can be simulated with pseudo-haptic feedback.

Hara [9] examined user weight perception when the heaviness of a virtual object suddenly changes using a haptic device, results indicate that users perceive a change in weight of the virtual object only when the difference between the initial and the actual weight is significative, it was concluded that when the user cannot perceive the change of weight, he/she may unconsciously adjust their muscle command to the weight change.

Uni-manual and bi-manual weight perception when lifting virtual boxes was evaluated by Giachristis [10], who proposed that accurate perception of simulated weight should allow the user to execute the task with high precision.The results indicated that bi-manually lifted virtual objects tended to feel lighter than the same objects unimanually lifted. Users seem to be five times less sensitive to virtual weight discrimination than for real weights.

Vo and Vance [11] examined the context in which haptic feedback affects user performance. In the weight discrimination task the user was asked to idendify the heaviest object of a couple of virtual models showed. The results obtained showed that users compared models in less time using haptic feedback than using only visual perception and that identification of weight is dependent on which hand was used to manipulate the object.

According to the previous research works, a method to evaluate user performance in virtual assembly tasks is by measuring the Task Completion Time (TCT). Several authors have observed that the weight of virtual objects is one of the most important factors that affect the TCT [7, 8, 9]. Thus, this work evaluates the effect of virtual weight on the TCT. An assembly task is used as case of study to compare the performance of virtual assembly vs. the real assembly in terms of the TCT.

3. System overview

A haptic virtual assembly system, named as HAMMS, has been developed and it is shown in Fig. 1. The HAMMS interface has been developed in Visual C++ and comprises the Visualization Toolkit libraries (VTK 5.8.0) and the Open Haptics Toolkit v3.0. Two physics engines, PhysX™ v2.8.4 and Bullet v2.79, have been integrated in HAMMS and the user is able to select any of them during run time. Single and dual haptic is provided using Sensable's Omni haptic device. One of the main characteristics of HAMMS is a control panel where the user can modify in real time simulation parameters; haptic properties like stiffnes, damping and friction; and physical properties like mass, restitution, tolerance, etc.

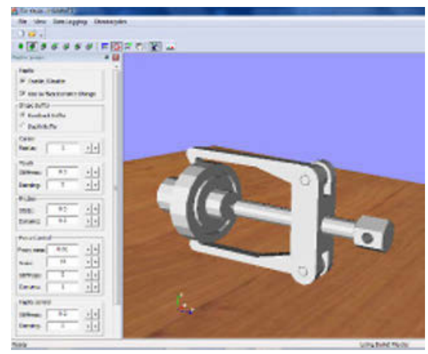


Fig. 1. HAMMS interface

The use of chronocycles [12] is also implemented in the HAMMS platform, allowing the user to graphically observe the path of the assembly once it is completed.

Two interaction phases are identified while the application is running: the first logs when the objects are only touched ("inspect") by the haptic proxy but not manipulated, the second phase is when the objects are being manipulated ("control") with the haptic device. In the "control" phase the physics model is attached to the haptic model by a spring – damper system and the graphic model is updated with the physic model (Fig. 2).

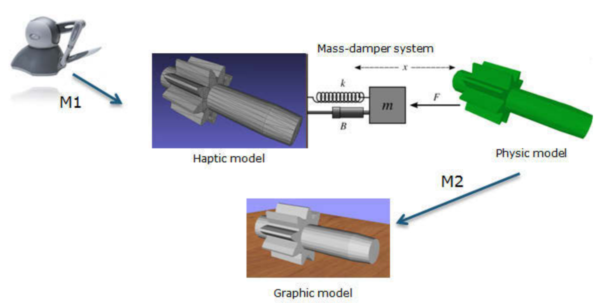


Fig. 2. "Control" phase of virtual objects

The use of the spring-damper model allows the calculation of force feedback that the user will feel when a collision occurs or when virtual objects are manipulated (weight perception). The values of spring constant and damping are determined empirically and adjusted so that smooth and stable movement of the manipulated part is obtained [5].

4. Experimental setup

The assembly task selected in this investigation was a gear oil pump. The pump comprises five parts: the housing, a big cog, a small cog and two figure-eight bearings retainers. The virtual and real pump components are shown Fig. 3. The virtual objects are imported into the HAMMS application as STL files.

(a) (b)

Fig. 3. Pump components, a) Virtual and b) real

Eight levels of weight, measured in Newtons (N), are defined for each pump component, L1 to L8, where L1 is the minimum weight and L8 the maximum weight in the virtual scene. The virtual and real weights are presented in Table 1. These virtual weights were obtained by scaling the density of the virtual objects. The maximum force suported by the Sensable Omni Device (3.3 N) was considered when assigning the weight level 8 to the heaviest manipulated object, the big cog. The housing is not considered because during the assembly process, real and virtual, it is the base part and remains static.

The real assembly was performed by 5 persons with each subject performing the task with one and two hands. The virtual tasks were carried out by an experienced user in both haptics and virtual assembly in order to avoid learning. The pump assembly was performed four times for each level of weight and using one and two hands. The virtual assembly tasks were performed using both physics engines, Bullet Physics and PhysX^{tm}, in order to observe the influence of different simulation engines on the assembly process.

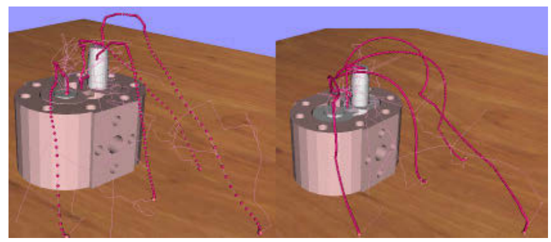
Table 1. Levels and weights (N) of pump components

Level	Housing	Big Cog	Small cog	Bearings
L1	0.02	0.02	0.02	0.02
L2	1.3	0.17	0.13	0.1
L3	3.34	0.41	0.34	0.29
L4	>4	0.82	0.66	0.51
L5	>4	1.11	0.9	0.69
L6	>4	1.64	1.31	1.01
L7	>4	2.23	1.81	1.34
L8	>4	3.24	2.71	1.47
Real	16.7	6.7	5.2	1.6

5. Results and discussion

The chronocycles employed in HAMMS offer a graphic representation of the trajectories and user haptic manipulations in the virtual environment. When a virtual object is being manipulated with the haptic device the movements are recorded and once the assembly has been completed chronocycles can be observed to analyse the manipulation of the object. Figs. 4 (a) and (b) show the chronocycles of the pump assembly task using level of weight L1and L8 respectively. The red spheres represent the path of the virtual objects when they were manipulated by the haptic device, and the distance between each sphere represents the speed of the motion; a low velocity is identified when one sphere is very close to the next one.

From observation, the initial manipulation of the object, when moving from its initial position to the target position, is faster at weight level L1 compared to level L8. This is verified from the chronocycles curves for L8, suggesting that larger inertia influences the assembly operations. With increased inertia in the virtual objects, the manipulation speed decreases, as it occurs in the real world, i.e. heavier objects are more difficult to manipulate.



(a) (b)

Fig. 4. Chronocycles using A) weight L1, B) weight L8

The task completion time in Fig. 5 shows the results obtained from a single-handed assembly task. In the case of the real assembly task, the TCT mean value for one hand was 37 seconds. The TCT of the virtual assembly task using the PhysX simulation engine is shown as the red dashed line, while the same virtual task but using Bullet physics is shown as the green dotted line. Both red and green lines represent the mean values for each level of weight.

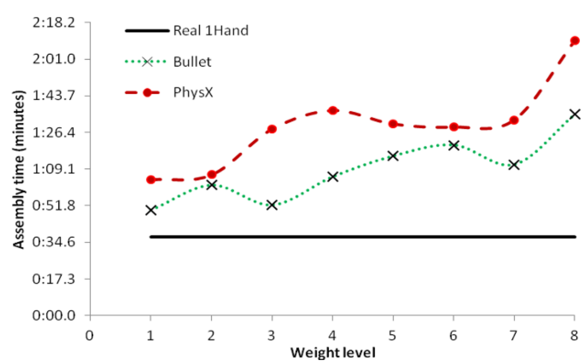


Fig. 5. Task completion time with one hand

From the results (Fig. 5) the minimum assembly time when using one hand corresponds to the weight level L1, where the weight of virtual components is minimal (0.02 N), only enough to keep the system stable. Using Bullet physics the minimum mean time was 49 seconds, with minimum TCT reported at 39 seconds. For PhysX the minimum mean value was 64 seconds and the minimal reported value was 59 seconds. The mean value for the task completion time (TCT) for one hand real assembly was 37 seconds and for two hands 27 seconds.

Figure 6 shows the results obtained with bi-manual assembly. The real process took an average of 27 seconds to complete. In the virtual experiments with two hands the minimum TCT value also corresponded to weight level, L1. Bullet physics posted a minimum mean time of 52 seconds, with a minimum reported assembly time of 44 seconds. In the case of PhysX, the TCT for weight level L1 was 75 seconds and the minimum reported TCT 61 seconds. A dip can be observed in weight level L6 for both simulation engines, Bullet and PhysX, this may be due to compensation of haptic stiffness; at weight level L6, the weight of all the models are above 0.88 N, that is the maximum continuous force for the Phantom Omni device; this value must not be confused with the maximum rendering force.

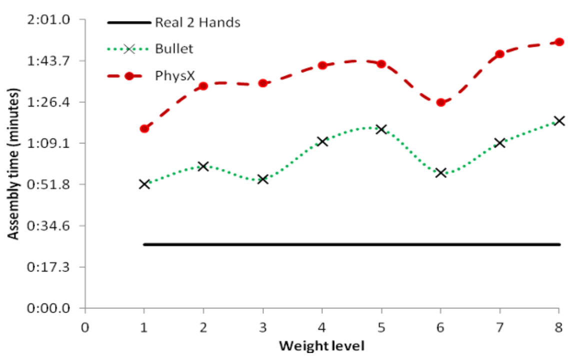


Fig. 6. Task completion time with two hands

The procedure to assemble the pump using two hands in the real world was very similar to the assembly in the virtual environment; two hands were used to align and fit the gears in the housing and bottom bearing. In the real assembly process, the TCT was smaller when using two hands than when using only one hand, however in the virtual environment the TCT using two haptic devices was greater than when using only one device. This difference may be caused by the collision response, such as sticky objects or unnatural reactions, when two objects are being manipulated. It was also observed that the fitting and aligning of the two gears was a difficult task in the virtual environment when using two hands. In general, it was observed that the time to complete a real assembly task is still smaller than the time to complete the same assembly task but in a virtual environment. Weight perception affects the TCT, as the weight of the virtual objects increases, the assembly time increases. Also, it can be said that the physics engine affects the performance of the assembly task.

6. Conclusions and future work

The effect of weight perception on human performance in virtual assembly environments enabled with haptics has been investigated. The results suggested that the performance of virtual assembly tasks, in particular the TCT, is directly affected by the weight of virtual objects; i.e. as the weight of virtual objects increases, the TCT will also increase. The chronocycles analysis showed that as the weight of the manipulated objects increases, the manipulation velocity decreases. Further investigation considers the analysis of the weight perception effect on the user by measuring muscle and brain activity in order to identify how the user reacts to different conditions on virtual assembly tasks.

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Impact of workers with different task times on the performance of an asynchronous assembly line

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Abstract. Assembly lines are often dependable on the human elements when an extended automation is not economically viable, even if technologically possible. Workers have variations in their performances which can mean they have a different average completion time and/or a different dispersion in the time they take to perform a task. Using simulation, these combined effects are tested in a three workstation asynchronous and unbuffered assembly line, in order to understand how the different combinations of performances affect the system output.

Keywords: assembly system, human-centred systems, asynchronous line

1. Introduction

The modelling and simulation of assembly systems have been specially focused on technological and operational aspects, in which operators are represented as resources performing defined tasks with variable availability and/or variable efficiency [1]. Depending on the cases, this approach might be sufficient on highly mechanised processes. However, there are assembly systems in which the tasks are mainly performed by workers, with little or no use at all of automation [2].

Workers are expected to present individual differences among them, represented by variations both on the average time to perform the assigned tasks as well as on the amount of variability on those times. When evaluating an assembly system performance, the task time variability has been modelled as a function of the task content or of environmental effects. Nonetheless previous research studies demonstrate that differences in task times are mainly caused by differences among workers, rather than by minor differences in tasks content or in the time period they are performed [3]. It is more likely to obtain an inaccurate estimate of system productivity if one assumes that all workers come from a pool represented by a single value or a single probability distribution.

Performance analysis was one of the first manufacturing systems applications of discrete event simulation (DES), and has proven to be one of the most flexible and useful analysis tools in this field [4]. In this paper, discrete event simulation is used to model an assembly system and test the influence of the different workers task times.

Data from an industrial setting is used as an example of the different task times, which could be found when performing manual high motor content assembly tasks. The observed performances, categorized in different classes (slower/faster; higher/lower variability), are tested in different scenarios of workers allocation in an unbuffered asynchronous assembly line with 3 workstations and are then compared to a scenario in which all workers perform, according to the “average worker”, with the same variability and average task time. An unbuffered system is subject to 'coupling effects', instances of idleness imposed on a workstation when it is 'starved' for available work or 'blocked' from passing completed work to the next station. Nonetheless, many assembly systems are required to hold minimal work-in-process inventories because of space or capital limitations [5]. The assembly line with 3 workstations limits the possible combinations (allocation of the 5 possible performances), while still has a central position to enable symmetrical allocations comparisons. The production of a given number of parts is simulated to assess the impact of the different scenarios in the assembly line performance.

2. Workers task times: Input data

Previous studies performed by the authors [6] indicate that the workers might have significant variations of both average time and variability when performing high motor content assembly tasks. Therefore, the worker performance can be measured in terms of deviations to the workstation expected values (the average time and average variability). A worker might have a task time which is slower or faster than the average and/or more or less dispersed than average. Given that, four types of performance can be considered in terms of deviations to the average values:

- The worker is slower completing the assembly task and the task times are more dispersed than expected;
- The worker is faster completing the assembly task and the task times are more dispersed than expected;
- The worker is faster completing the assembly task and the task times are less dispersed than expected;
- The worker is slower completing the assembly task and the task times are less dispersed than expected.

According the referred study [5], several workers had their times sampled on the industrial setting and their performances were classified according to their deviation to the overall performance - Expected (E). Table 1. presents the 4 established performance classes with the deviations, (*x, y),* to the overall average and dispersion task time, that characterize the average task time and dispersion within each performance class.

Table 1. Average Performance Deviations to (E)

Class of Performance	Performance deviations (*x*;*y*)
Quadrant I (QI)	(+15.9 %; +26.4%)
Quadrant II (QII)	(-4.5%; +13.3%)
Quadrant III (QIII)	(-11.3%; -21.4%)
Quadrant IV (QIV)	(3.8%; -9.1%)

During the data collection it was observed that the workstation with the given type of assembly tasks of high spelling motor content, had an expected average completion time of 15 sec and a standard deviation of 1.95 sec. Based on the (*x*;*y*) deviations, the type of workers performance can be assessed and compared to the expected average time and standard deviation. Using a triangular centred task time distribution, the minimum, average and maximum times for each performance is calculated and used as input to the simulation study (Table 2). Depending on the performance class, the time distribution can shift and/or can be wider or narrower than the expected one.

Table 2. Task times input data

Class of Performance	Min. [sec]	Average [sec]	Max. [sec]	Standard Deviation [sec]
E	10.22	15.00	19.78	1.95
QI	11.35	17.39	23.43	2.46
QII	8.91	14.33	19.74	2.21
QIII	9.55	13.30	17.06	1.53
QIV	11.23	15.58	19.92	1.77

3. Simulation model

To test the impact of having significantly different task times, it was considered a serial assembly line, with three workstations (as depicted in Fig.1). Each workstation has one dedicated worker. The part transfer between workstations is done asynchronously. This means that when the worker finishes the assembly tasks on his workstation, transfers it to the next workstation if it's idle (waiting for a part). If the next workstation is not idle (is either working or blocked), then the workstation becomes blocked, the worker has to wait and cannot accept any other part. The first workstation is never waiting and the last station is never blocked. There isn't the possibility to buffer parts between workstations. Also, in order to isolate the performance variations effect on the system, the work content in each workstation is the same, meaning that the line is perfectly balanced. Any unbalance will then be caused by the workers performance variations.

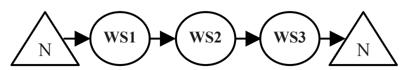

Fig. 1. Simulated assembly line

The simulation model was implemented on MATLAB, using Object Oriented Programming (OOP). The program tests all the possible combinations of workers task times. To test the different scenarios of performance allocation, the model was simulated until it produced 1800 parts (N).

For assembly line design purposes it is important to make sure that an assembly system is able to achieve a given output rate (average number of parts assembled by unit of time). However, the output variability also plays an important role on the daily planning and control of the system [7]. In this paper, the focus is given to the average inter-departure time (IDT) and the inter-departure time variability (SD) as measures of the system performance, as well as to the total required time to produce the N parts. The developed model records each time a part leaves the system, therefore the IDT is obtained by subtracting the successive times in which the parts leave the system. The SD is obtained by calculating the average of the variances obtained for each run (out of 10) of 1800 produced parts and applying the square root to this value. Since a warm-up period is not considered, the first IDT value will be larger than the following ones.

4. Results

In section 4.1 the results for all the workers with the same task time distribution are analyzed. In the following sections the focus is on the cases where task time distributions differ.

4.1. Every worker with the same task times

Fig. 2 represents the distribution of the system inter-departure times obtained with the simulation runs for all the workers with the same class of performance. In each 1 sec interval the average frequency with which a part left the system was calculated. It can be observed that the interaction of the several workers in this system configuration, introduces some positive skewness on the output time distribution due to blocking and waiting times, which increases the probability of the part spending more time in the system and therefore increasing the IDT.

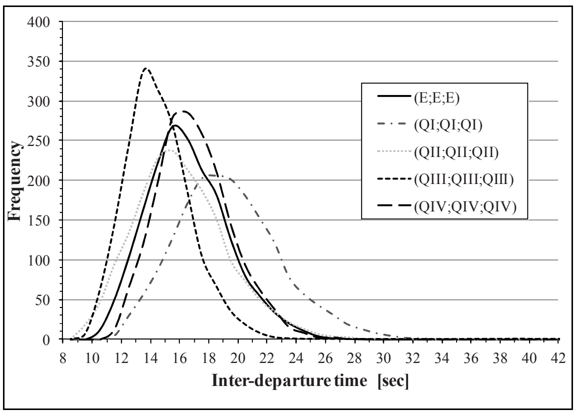

Fig. 2. Histograms – Workers with the same class of performance on every WS

The increase on the average task time results in an increase of the average system IDT (see Table 3). The same happens with the variability. If (all) the workers have a performance with higher average times and higher variability, the system IDT will also be higher and with higher variability (SD). The best possible scenario is having all workers with QIII performance and the worst is having them with QI performance. Nonetheless, if scenario (E;E;E) and (QII;QII;QII) are compared it can be concluded that the allocation of workers with QII performance (slightly faster but with task times more dispersed) increase the line performance since the system would produce the same amount of parts within less time. However, in reality workers seldom have all the same performance.

Table 3. Results – Workers with the same type of performance on every WS

Class of performances (WS1;WS2;WS3)	IDT [sec]	SD [sec]	Time Span [h:min]	Time Deviation [%]
(E;E;E)	16.55	2.88	8:17	-
(QI;QI;QI)	19.34	3.64	9:41	17%
(QII;QII;QII)	16.08	3.23	8:03	-3%
(QIII;QIII;QIII)	14.51	2.28	7:16	-12%
(QIV;QIV;QIV)	16.98	2.64	8:30	3%

4.2 The effects of allocating one worker with worst performance (QI), or best performance (QIII)

Table 4 presents the results obtained by allocating one QI or QIII worker type in the several line WS positions. Type E operators are allocated to the other two WS.

The simulation results show that, if there is one worker with the worst performance class - QI, while the others have an Expected (E) performance, the output of the assembly line depends on the workstation where he/she is allocated. The higher IDT is obtained when he/she is allocated to WS2 (E;QI;E), however (the SD is not the lowest). In this scenario, there are more chances of increasing the blocking situations on WS1 (that the worker cannot pass his/her output to WS2) and waiting in WS3 (in which the worker is waiting for inputs). On the other hand, when the results are analyzed in terms of total time to produce the 1800 units, then the time deviations, when compared with the (E;E;E) scenario, are very similar. The SD is lower for the (E;E;QI) scenario, meaning that the system output flow will be smoother when compared with the other scenarios, namely with scenario (QI;E;E).

In the case of having one worker with the best performance then it will have a more positive impact (IDT and SD reduction) when he/she is allocated in WS2, but the difference between putting him/her in WS1 or WS3 is larger than in the previous case.

Overall, if there is one worker with a worse performance among others that are representative of the overhaul population of workers (expected behavior), wherever he/she is allocated, the assembly system IDT will deviate at least 8% from the one expected when all the workers belong to E type performance (scenario E;E;E). If there's one worker among the others (E type ones) that has a better performance, the amount of time required to produce the total amount of parts will reduce a maximum of 3.7% if he/she is allocated to WS2, otherwise it's only possible to obtain a 2.3% total time reduction.

Table 4. Results – One worker QI/QIII among workers with the expected overall performance

Class of performances (WS1;WS2;WS3)	IDT [sec]	SD [sec]	Time Span [h:min]	Time Deviation [%]
(QI;E;E)	17.88	3.40	8:57	8.0%
(E;QI;E)	17.99	3.38	9:01	8.7%
(E;E;QI)	17.90	2.84	8:58	8.1%
(QIII;E;E)	16.18	2.61	8:06	-2.3%
(E;QIII;E)	15.94	2.60	7:59	-3.7%
(E;E;QIII)	16.17	2.97	8:06	-2.3%

4.3. Allocations for the lowest/highest inter-departure variability

The performance of the assembly depends not only on its output rate but also on the smoothness of its behaviour. So, to identify the workers allocation that result in smaller variability of the output several simulation runs were conducted. The results indicate that the SD is lower in the (QIII;QIII;QIV) scenario, and not with the (QIII;QIII;QIII) (see Table 5) . This means that allocating a worker with a performance with more variability and slower when compared with QIII will result in lower variability ouput during the production of the 1800 parts. This happens because the worker in WS3 has a performance with a higher average time therefore the variability from the workers in WS1 and WS2 will be absorved. Note that if there was a QI worker in WS3, then the the output IDT would be higher. Also in this scenario it's required more time to produce the parts than with (QIII;QIII;QIII).

The combination with the highest output variability, is the (QI;QI;QII). In this case the worker in WS3 has a lower average time, causing the SD increasing. Again, there are gains in terms of the amount of time required to produce the 1800 parts when there's a QII performance type instead of a QI performance type on WS3(these effects are can be seen on Fig. 3).

Table 5. Results – Higher/Lower inter-departure variability

Type of performances (WS1;WS2;WS3)	IDT [sec]	SD [sec]	Time Span [h:min]	Time Deviation [%]
(QIII;QIII;QIII)	14.51	2.28	7:16	-12%
(QIII;QIII;QIV)	15.82	2.01	7:55	-4%
(QI;QI;QI)	19.34	3.64	9:41	17%
(QI;QI;QII)	18.86	4.18	9:27	14%

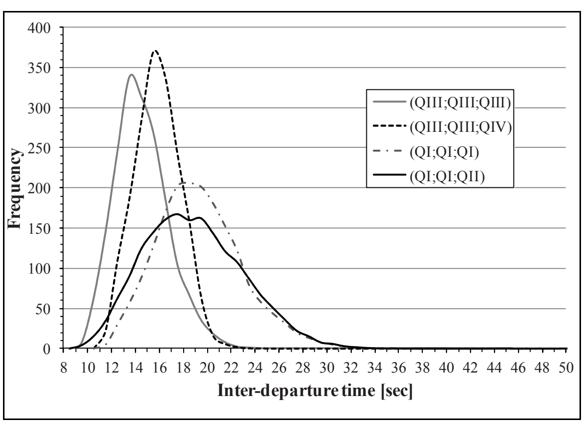

Fig. 3. Histograms – low/high SD output

5. Conclusions

Workers task times can vary significantly one from the other, both in terms of average and dispersion of task times. Considering five classes of workers performances, a three workstation assynchrounous unbuffered assembly system was simulated with different combinations of performances. Results indicate that the position in which the best/worse time performing worker is allocated has a small impact on the system output. Nevertheless, if there's one worker with a worse performance than the others, the system output can be significantly affected, specially if he/she's allocated to the middle workstation. Having one worker which outperforms the others doesn't have such a large (positive) impact. In terms of inter-departure variability, it will be reduced if the best two workers are allocated to the two initial workstations and in the third, there is a worker with a slightly larger average task times. This inter-departure variability reduction will be at the "cost" of increasing the inter-departure time, and consequently the amount of time to perform the total number of parts. Overall, the differences on workers task times can have significant impacts on the output performance of manually operated systems, and should be taken into account when managing such systems. Nonetheless, further studies should be made considering system parameters variations such as work in process buffers, work tasks transfer between workstations, among other factors. Namely, an important extension to this research will be the impact of different task times in longer assembly lines.

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An integrated data model for quality information exchange in manufacturing systems

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Abstract. Quality measurement is an integrated part of modern manufacturing systems. As the manufacturing industry has entered a digital and virtual era, information technology has become increasingly important for both machining and measurement systems. Effective information sharing and exchange among computer systems throughout a product's life cycle has been a critical issue. The quality measurement industry and standards organizations have developed several successful standard data models to enable standardized data. However, these standards have very restricted focus. From late 2010, the Quality Information Framework (QIF) project was initiated by the Dimensional Metrology Standards Consortium (DMSC) with the support of major North American quality measurement industries. This project aims to develop an integrated Extensible Modeling Language (XML) data model for the entire quality measurement chain. It consists of five application area schemas and a QIF library with nine supporting schemas. This paper introduces the scope and data model design of QIF. A pilot test project using the recently completed QMResults schema for the exchange of inspection result data is also presented.

Keywords: Quality Information Framework (QIF), manufacturing quality systems, information modeling, data model, XML schema, measurement features, characteristics, ASME Y14.5

1. Introduction

In the past two decades, the manufacturing industry has undergone drastic changes: digitization of manufacturing process chain, globalizing supply chain, fast technology development, and escalating complexity of products. For major manufactureres, such as airplane manufacturers, automobile manufacturers, etc., the technology bottleneck is shifting towards manufacturing systems integration and enterprise systems integration. The reason for this situation is that hardware and software systems generally process input and output data in their own data formats. A typical manufacturing chain often consists of (from upstream to downstream) Computer-Aided Design (CAD) software, Computer-Aided Manufacturing (CAM) software, Computer-Aided Inspection Planning (CAIP) software, and Statistical Process Control (SPC) software. The information can not flow directly from upstream to downstream without data translation. Translation is not only time and money consuming but also results in loss of integrity of information. Furthermore, the information exchange between CAD systems from different vendors also needs data translation. There are many research efforts in standardizing data exchange within manufacturing systems. This paper will present a new effort aiming to develop a consolidated data model library for the exchange of quality data within manufacturing systems. This effort is called the Quality Information Framework. A primary benefit of this research is to reduce resources needed for systems integration in all manufacurting industries that implement dimensional metrology systems. In 2006, the automotive industry alone reported that costs due to translation of measurement data between manufacturing systems amounted to over $600 million annually [1]. Moreover, adopting QIF will facilitate commercially available components to be interoperable allowing users to buy the products that suit their individual business models.

2. Flow of information in manufacturing quality systems

Manufacturing quality systems comprise the software and hardware used for quality control in a manufacturing process. Quality control is intertwined with machining activities in a manufacturing process. As shown in Fig. 1, there are four main elements in a typical manufacturing quality system: measurement planning, inspection programming, measurement execution, and quality results analysis and reporting [2]. The solid lines in Fig. 1 represent the common information flow in typical manufacturing quality system; while the dotted lines represent alternative information exchange. Product definition information is the highest level upstream information flowing into any manufacturing quality system. It is the combined information of product design information (generated through CAD software) and multiple quality management requirements such as Product Lifecycle Management (PLM), First Article Inspection (FAI) requirements, Enterprise Resource Planning (ERP) information, etc.

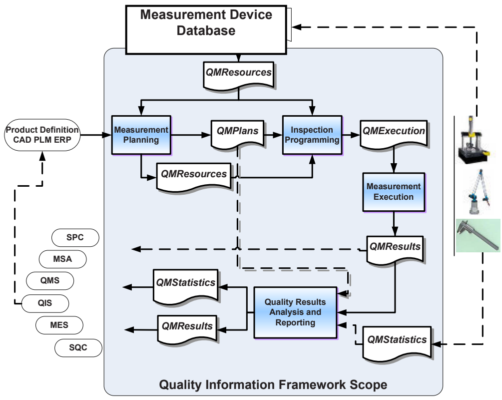


Fig. 1. The scope of QIF

The measurement planning activity receives all the information mentioned above and takes into consideration of the availability of quality measurement resources to generate measurement plans. Descriptions of all inspection resources in a facility, as well as resources assigned to specific plans are formated according to the *QMResources* data model. High-level plans, formatted according to the *QMPlans* data model, identify the measurement features, their characteristics, and the measuring sequence. The function of the inspection programming activity is to generate the machine-level measurement plan for execution based on available measurement devices. Low-level plans, formatted according to the *QMExecution* data model, provide detailed measurement operation information (i.e. probing points, scanning routes, etc.). The function of the inspection programming activity is to generate the machine-level measurement plan for execution based on available measurement devices. Most coordinate measuring machines (CMMs) require the execution commands to follow specific proprietary format for their controllers. This process is carried out by the measurement execution activity, whose responsibility is to interpret machine-level measurement plans, give equipment level commands to specific CMM control units, collect point data, fit features to data, and output feature and characteristic data formatted according to the *QMResults* data model.

Once the machine-level measurement plans are executed, the measurement data, either raw data or pre-processed data, is collected, reported, and analysed. The collection and the analysis of multiple part inspections are formatted according to the *QMStatistics* data model. The purpose of quality control is not just to judge whether a product meets the functional requirements of the design after it is manufactured. The data gathered through quality control (both in-process and post-process) can also be used to assess the performance of the machine, to judge the quality and the efficiency of the machining process plan, and to trace any unexpected anomalies during the manufacturing process. Through analyzing measurements data, statistic process control can provide feedback to upstream processes, such as CAD design, statistical quality control (SQC), etc., to improve the production of future products.

3. QIF scope and schemas

There are multiple international standards effort trying to develop suitable data model to overcome the interoperability barrier in manufacturing quality systems. Reviews of these international standards efforts can be found in references [2-6]. Each effort focuses on a narrow slice of the overall manufacturing quality system. Most of them developed independent data models, which often overlap with other models, contributing to interoperability problems. The QIF effort was initiated by the DMSC [7] aiming to overview the existing standard data models in manufacturing quality systems to develop a consolidated data model to cover the entire manufacturing quality chain. The contents of the QIF data model was designed to encode all information in ANSI/ASME Y14.5 2009 [8] and the Dimensional Measuring Interface Standard (DMIS) 5.2 [9]. The scope of QIF covers the five interfaces shown in Fig. 1.

3.1. QIF schemas

The current release of QIF Version 0.9, has the QMResults application area schema and nine supporting schemas complete and released for beta testing. The QMPlans schema is in draft shape and the remaining three schemas have been planned to be developed in the near future. The supporting data model schemas, collectively called the QIF Library, are named as following:

- **CharacteristicTypes** - defines quality requirement information, including geometric dimensioning and tolerancing (GD&T) tolerance, attribute tolerance (i.e., Go/No-go gaging requirements), and user defined requirements.
- **FeatureTypes**- defines all 28 types of measurement features found in DMIS 5.2.
- **ConstructedFeatureTypes**-defines methods of constructing measurement features.
- **Units** - defines units for values of angle, area, force, length, mass, pressure, signed length, speed, temperature, and time.
- **MeasurementDevices**- defines the basic information regarding measurement devices such as

probe accuracy, stylus length, touch-triggering force, etc.

- **Traceability** - defines traceability information within the manufacturing quality system and with the machining process, such as part serial number, machine tool number, process id, etc.
- **Transforms** - defines coordinate systems transformation information.
- **PrimitiveTypes -** defines primitive common information that is used by other application area schemas but is not covered in the above supporting schemas, such as degree of freedom, notes, measure point, etc.
- **QIFTypes** - defines non primitive common information used by application area schemas but not covered by the above supporting schemas, such as file type, model entity, software type, etc.

One of the five application area schemas, QMResults, has been built and is believed to be technically complete for the reporting purposes it was built to serve. It is expected that testing and debugging will add only minor items related to those purposes. Testing the QMResults schema began in October 2011, when sample test files were first built. A second application area schema, QMPlans, has been drafted but, as of February 2012, is not technically complete.

3.1.1. Semantic Connecting Types Using Identifiers

In QIF each characteristic and feature is defined using four ***aspects***: definition, nominal, actual, and instance. These have identifiers and are connected by references to the identifiers. Notes may be attached to any of the four aspects. Take features as an example:

- A **feature definition** includes information that is independent of the position of the feature - the diameter of a circle, for example. A single definition can be referenced by many nominal features. Only nominal features reference feature definitions.
- A **feature nominal** defines a nominal feature by referencing a feature definition and providing position information - the center of a circle and the normal to the plane of the circle, for example.
- A **feature actual** defines an actual feature that has been measured or constructed. A feature actual may optionally refer to a feature nominal and is expected to do so if there is a nominal feature. There may not be a nominal feature if the actual feature is built during a reverse engineering process.
- A **feature instance** represents an instance of a feature at any stage of the metrology process - before or after a feature has been measured. The feature instance must reference a nominal feature or an actual feature. If an actual feature is referenced, the corresponding nominal feature (if there is one) may be found through the actual feature. If a feature is measured several times, it is expected that a feature instance will be defined for each measurement and will have a different actual feature for each measurement.

In XML data files, relationships between the four aspects are expressed using strongly typed links, whose types are related to the data elements they are linking. This use of typed links, or references, will allow standard XML data file validation rules to enforce integrity of the relationships. A more technically detailed discussion of this technique can be found in the design and usage guide of QIF, which will be published soon by NIST.

3.1.2. QIF Validation to ANSI/ASME Y14.5 2009

The CharacteristicTypes schema represents the entire GD&T requirements defined in ANSI/ASME Y14.5 1994 standard. In order to make QIF compatible with the newly published 2009 version, a validation effort was carried out to update CharacteristicTypes with all the new GD&T requirements. Table 1 lists some of the new items defined in the 2009 version. Some of the new items are accompanied with new symbols. This validation process is still ongoing.

4. Case Studies for validating QIF

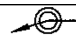
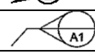
In September 2011, the QMResults schema Version 0.9 was released by the QIF QMResults working group. Since then, a series of validation tests have been carried out to evaluate correctness and completeness of the specification. The first step of the validation was to create QMResults data files containing simulated measurement results for sample parts. The validation requirement is that the data files contain all measurements described by part drawings, and that the XML data files be correct according to the QMResults schema. Part drawings shown in Fig. 2 are:

- A CMM calibration master ball
- Advanced Numerical Control (ANC) 101 example part
- Sheet metal scanning measurement example part.

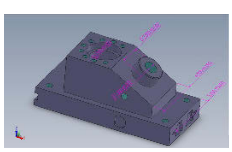
5. Conclusions

Based on the development of QIF to date, the DMSC believes that a complete set of specifications will facilitate simple integration of commercial software solutions for manufacturing quality systems. Exchange of quality data in standard formats is judged to be a good solution to achieving interoperability of multi-vendor software components. Benefits accrued to manufacturers should include flexibility in configuring quality systems and in choosing commercial components, and effortless and accurate flow of data within factory walls as well as with contractors and suppliers. In order to facilitate and encourage software applications that manipulate QIF formated data, DMSC proposes, in the near future, to create software libraries that write data into QMResults XML files (serialization), and/or read data from QMResults XML files (deserialization). This software development will be an open source, public domain project so members of the manufacturing quality community can suggest improvements or improve the code for the benefit of all users.

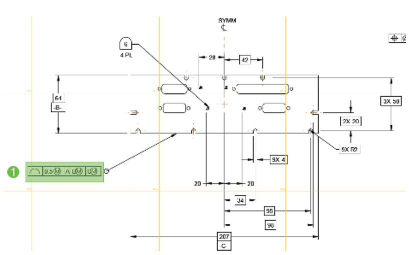
Table 1. New GD&T information in ASME Y14.5 2009

New Items	**Symbols/ Indicator**
All over	
Movable datum targets	
Unequally disposed profile	Ⓤ
Independency	Ⓘ
Continuous feature	⟨CF⟩
Datum translation	▷
Maximum Material Boundary (MMB)	Ⓜ
Least Material Boundary (LMB)	Ⓛ
Regardless of Material Boundary (RMB)	N/A
Nonmandatory (MFG DATA)	N/A
Datum feature simulator	[ ] ,BASIC or BSC
Explicit degrees of freedom for datum reference frames	[u,v,w,x,y,z]
More than two tier composite position control frames	N/A
More than two tier composite profile feature control frames	N/A

a) a CMM calibration master ball



b) ANC101 example part



c) Sheet metal scanning measurement example

Fig. 2. QIF validation case studies

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Bayesian network modeling of machine breakdowns

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Abstract. This paper considers a common problem that all industries contest with in practice i.e. the breaking down of machines that influence production and cost directly. In a majority of industrial applications, acquiring optimum utilisation of all available resources for existing and future predicted demand is a major function throughout all the levels of management. This paper uses a number of analytical tools and software that support one another i.e. Witness Simulation, Bayesian Network Modelling and Hugin Software. The use of expert experience and knowledge has been incorporated throughout the study as it is vital to model building and greater understanding of machine breakdown. This study uses discrete event simulation and Bayesian network modelling collectively to understand machine breakdowns to increase efficiency within a cement manufacturing plant i.e. the Crusher Machine. The Bayesian network modelling implemented by the Hugin Software is used to generate probabilities which are transferred into a discrete event simulation model using Witness Software based on the historical data, expert knowledge and opinions. The model simulates the three parameters of the machine life based on consumption of each parameter. This is translated into a probability failure rate that changes as the model is running. The model demonstrates decisions based on the probability of failure from the Bayesian model and based on life consumption of the different variables in the simulation model.

Keywords: Witness Simulation; Hugin Software; Bayesian Network Modelling, Cement.

1. Introduction

This paper considers analytical tools such as the Bayesian Network Modelling that is aided by the Hugin Software and Witness Simulation to understand machine breakdowns. This paper aims to model and reduce the effects of breakdowns that occur within a single crusher machine using the analytical tools. The development of the model will result in different probabilities of failures and to explore different approaches in calculating the most likelihood of a failure occurrence.

2. Methodology

Bayesian network modelling (Fig. 1) is a mathematical tool used to model uncertainty in a chosen area or a system, it can help identify and highlight links between variables [1]. The recognition of important variables as well as consideration of other influencing factors that seem to exist within the system is integral to the Bayesian approach. The Hugin software (Fig. 2-5) interprets historical data and expert knowledge into a probabilistic figure that shows when the likelihood of machine failure may occur, according to the parameters that exist based on the nodes and their dependencies. Hugin applies snapshot results i.e. the results indicate specific circumstances based on parameters, they are not continuously changing data but have to be changed manually to derive different results.

The role of Witness Simulation is to evaluate alternatives that either support strategic initiatives, or support better performance at operational and tactical levels [2]. Simulation provides information needed to make these types of decisions. The simulation approach supports multiple analyses by allowing rapid changes to the models logic and data, and is capable of handling large, complex systems such as a manufacturing facility. [3]

The Bayesian and Hugin approach is outlined in six steps that need to be followed in order to achieve the best results with the collated data. The six steps are as follows:

1. Establishing relevant and accurate information
2. Establishing nodes with dependencies
3. Establishing of CPT (Conditional Probability Table)
4. Normalise Probability
5. Propagate Evidence
6. Model Validation

The crusher machine is dependent on 3 parameters that exist and hence have influencing affects on the generated probability. In order to calculate the probability of the ‘failure’ of the crusher machine the chain rule must be applied. Given the above nodes and dependencies, the outcome or probability generated by the Hugin software is as follows shown in Fig. 6.

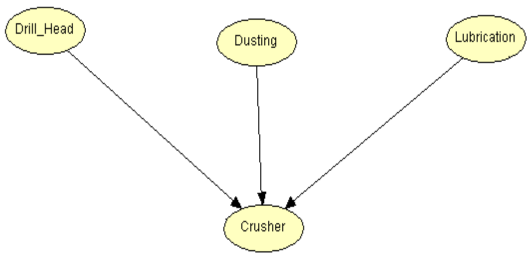

Fig. 1 Bayesian Network Modelling of a Crusher Machine and Parameters

Drill_Head	
used	70
Remaining	30

Fig. 2. Drill Head state

Dusting	
used	60
remaining	40

Fig. 3.. Dusting state

Lubrication	
used	50
remaining	50

Fig. 4.. Lubrication state

Drill_Head	used				Remaining			
Lubrication	used		remaining		used		remaining	
Dusting	used	remaining	used	remaining	used	remaining	used	remaining
Failure	100	75	62.5	50	37.5	25	12.5	0
Working	0	25	37.5	50	62.5	75	87.5	100

Fig. 5. Crusher Machine Parameters CPT

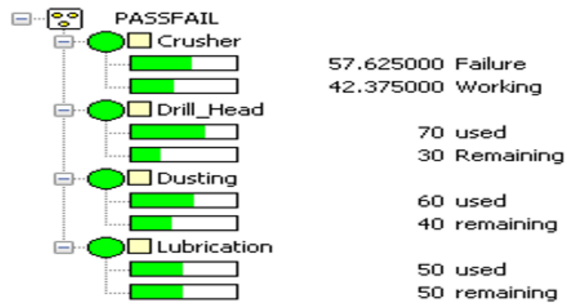

Fig. 6. Hugin results for Drill Head, Dusting, Lubrication and Crusher.

3. Witness Simulation

The Witness simulation software uses basic elements, together with distributions and timing inputs to replicate an accurate model. The distributions are then used to influence certain factors to acquire a certain result. The basic elements to simulate the models are as follows and can be seen in Fig. 7.

Entities represent parts that flow through the model, in this case, it will be the existing parameters. *Activities* represents a station where a task is completed. *Queues* are a point where an entity is held until the entity is required or needed, or even a point where a desired waiting time can be applied. *Resources* are the labour required to perform a desired activity.

For the ease of implementing, the three stated parameters into witness, all three parameters are now based on an estimated **LIFE, "***USED"* and "REMAINING", this represents each parameters usage that has been derived from historical data and with the use of expert knowledge. This usage rate has been attributed with "life span", this is the estimated life a parameter has and can be utilised until a change or repair is needed.

Once the overall life span has been reached, then only certain tasks need to be carried out i.e. the drill head according to historical data needs to be changed every 7 days hence the life span is 7 days/10080 minutes, the dust builds up within the machine and can cause disruption or unexpected errors if not cleared every 2 days/2880 minutes hence this is the life span of the dusting. The lubrication of the required mechanisms which exists starts to dry and cause friction if not lubricated every 3 days/4320 minutes.

The model developed aids logical understanding by the creation of the two variables per parameter, "Used" and "Remaining", as time/usage is being consumed, elapsed time will increase and the remaining time will decrease simply because the lifespan of the parameters are coming to an end. The model is shown in Fig.7 as well as the variables developed to generate the probability of failure.

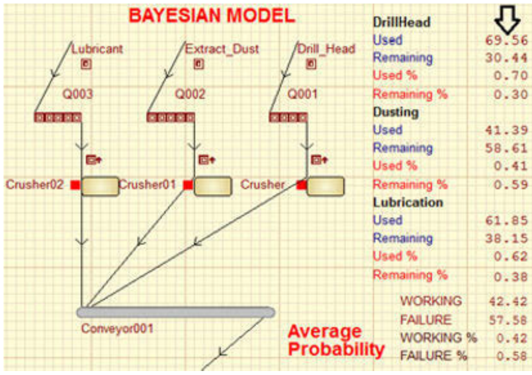

Fig. 7. Bayesian Model

The parameters do however require attention as they reach maximum life span and need adhering to; however, if two or three of the parameters almost reach the end of the life span simultaneously, this added together as a whole can easily cause breakdowns as more than one parameter has reached near the maximum usage. This is based on historical and expert opinion of the machinery.

4. Conclusion

After implementing and making use of the above analytical tools, the model developed by Witness Simulation shown helps consider many factors when simulating and approaching breakdowns. These tools aid understanding and enable better judgement to be made by the user, almost like a decision making tool as all the parameters and variables that do exist are based on legitimate reasoning that has been aided via many consultations with experts within the field. The applications of the above analytical tools result in an increase in logic being applied to the model and therefore increasing the validity of the model. These tools also help to generate and investigate different scenarios by using the different tools against each other. The main purpose of the paper is to achieve a reduction in breakdowns via the use of the above tools as described, the mean time between failure (MTBF) according to historical data is between 9000 and 9500 minutes. This means the crusher machine failure occurs approximately every 6.25 days to 6.59 days, a model was developed to understand the affects thereof. This was not a logical approach according to experts in the field, as the processing of cement and the site has many machines and cannot function effectively if machines breakdown once a week on a constant basis.

The probability of failure developed by the Bayesian approach in practice, where the probability has surpassed the 95% threshold indicated by the implementation of the rule, and this 95% threshold was decided with the consultation of experts and research. This 95% enabled a slight flexibility as different parameters had their own consumption rates as well as enabled deterioration of parameters to be considered. The results of the simulation model can be seen in Table 1 and 2. Table 1 shows the results of the model after 30 days and Table 2 shows the same result but upto the time a breakdown occurs according to the Bayesian approach to show the difference.After running the model for 61444 minutes a breakdown occurs compared to 7 breakdowns of the MTBF model.

The Bayesian model takes into consideration all the existing parameters, here the model does not breakdown according to the mean time between failures (MTBF), and this has now been totally eliminated. The Bayesian model, models the information that has been derived from the research and experts. [5]. Now the breakdown occurs when all three parameters combined usage rate is above the 90% threshold mark, this is according to expert knowledge where the deteriorations of individual parameters and the reduction in quality starts to appear. [6, 7]. This does not result in the machine breaking down however when all three parameters simultaneously reach the threshold it should develop into a breakdown.

The average probability of failure in the model is represented by ***WORKING*** shown in Fig. 7**,** this is to enable the machine to breakdown when the average is above the 90% threshold and below 95%. However as discussed above, this was not so logical simply because two parameters increase in usage rate can easily increase the average, this may mean that at no particular time all three parameters surpass the 90% threshold but rather they help each other to reach the average threshold. The machine breaks down according to the average rule as implemented however, when the parameters are considered it can be seen, the first parameter that has the longest life span i.e. Drill Head has only been used 83.80%, the other two parameters have helped increase the average, Dusting has been used 91.22% and Lubrication at 95.07%.

This also had to be verified and validated with the Bayesian model to see if the average worked in correlation to the failure developed by the Hugin software. shows the results, when exactly implemented into the software; the average failure is 90.01% in the simulation model whereas the failure rate developed by the Hugin software is 86.15%. This showed a significant difference in the results that were developed.

Table 1. 30 Day MTBF Results

30 Days/ 43200 minutes	MTBF Model	Bayesian Model
Drill Heads replaced	4	4
Dusting carried out	14	14
Machine Lubricated	9	9
Total BREAKDOWNS	5	2
Total inspection time	1111.7	1553
Total Repair Time	1518	589
Total Time Lost	2629.7	2142

From the results in Table 1 it can be seen, although the number of tasks carried out remain the same, total breakdowns differ i.e. MTBF has five breakdowns whilst the Baysain has two, further the inspection times differ indicating the bayesain model takes extra time in general inspection and welfare of the machine.

Table 2 shows the correlation of the influencing factors to that of the breakdown. Here, the five breakdowns of the MTBF model have been used and the parameter usage percentages can be seen in order to examine whether the breakdown occurs for a due course according to influencing parameters or simply due to the historical data from which the MTBF has been derived. Table 2 shows clearly, when all five breakdowns occur, the influencing parameters usage percentages are far from being consumed fully. Only breakdown four shows that dusting has been used 100%, indicating dusting is required as the other parameters still have majority of the lifes reamining. The bayesian model in Table 2 indicates a very high usage rate for all three parameters indicating the occurance of a breakdown, all three paramters ar above the 90% threshold as discussed earlier on in the conclusion.

Table 2. Usage Rate of MTBF & Bayesian Parameters

MTBF	Time	Drill Head Used %	Dusting Used %	Lubrication Used %
Breakdown 1	4544	45	57	5
Breakdown 2	13578	31	67	13
Breakdown 3	22612	16	78	21
Breakdown 4	32005	5	100	37
Breakdown 5	41212	88	17	49

Bayesian	Time	Drill Head Used %	Dusting Used %	Lubrication Used %
Breakdown 1	8623	90.55	97.33	99.14
Breakdown 2	32456	97.04	90.03	99.65

The bayesian model shows an absolute change in results from that of the MTBF model based on the consumption of parameters. This results in the machine breaking down from once a week according to the MTBF model to a possible breakdown of once every 2 weeks based on Bayesian model. This indicates a definite reduction in machine breakdowns based on the condition of key influencing factors that is not considered by the MTBF appraoch.

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Exposing human behaviour to patient flow modeling

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Abstract. Patient flow models have been universally used for planning health services for both acute and chronic patients. These models invariably assume patients are homogenous and events follow traditional queuing models. These techniques are useful for examining patient flow in large population groups where Markov assumptions, or simple extensions of these, can be made. However it is realised that such assumptions are not necessarily representative in cultures and communities that do not adhere to queuing policies particularly in developing countries. This paper explores the need to consider human behaviour within a patient flow model and reports on a study that identifies some of the critical factors that a patient flow system must take into account when planning and implementing health services in developing countries. The case study explores behavioural attitudes from hospital staff and patients and its impact on the patient flow system using telephone interviews and questionnaires with staff who work in the Emergency Department (ED) at Tripoli Medical Centre (TMC). The most important result of the study is staff believe that the presence of difficult behaviour of patients is a main reason for the delay and weakening of service quality levels. Other interesting observations have been found that will be useful to health service planners in developed and developing countries.

Keywords: Patient flow; human behaviour**;** emergency department ED overcrowding.

1. Introduction

An Emergency Department (ED) is a medical treatment facility, specialising in the acute care of patients who attend without a prior appointment having been made **[1]**. The department deliver a range of treatments covering a vast arena of different injuries and illnesses; importantly, some of these may be considered life-threatening, and may therefore necessitate immediate, urgent action. Nevertheless, EDs are experiencing many different obstacles and issues owing to the fact that there has been a significant surge in patient demand; this has subsequently induced the need to ensure services and their overall quality is improved. Within hospital emergency departments, one of the most significant, urgent operational difficulties is patients overcrowding, which is recognised as threatening public health and patient safety **[2].** Markedly, overcrowding is commonly considered as a circumstance wherein there are a greater number of patients than treatment beds and staff, and also where waiting times necessitate patients to endure long delays. The increase in the ED overcrowding problem has motivated researchers to delve into the issues surrounding the causes and effects, as well as how to establish a solution to this problem. Previous studies have listed the most common causes leading to overcrowding: an overall increase in patient volume, increased complexity and acuity of patients to the ED, a lack of beds for patients admitted to the hospital, avoiding inpatient hospital admissions by intensive assessment and treatment in the ED, delays in the service provided by radiology, laboratory, and ancillary services, shortage of nursing staff and/or physician staff, and a shortage of physical space within the ED [3,4,5]. Furthermore, there has been much published in the academic literature surrounding the consequences of ED overcrowding, such as increased risk of clinical deterioration, prolonged patient wait times, subsequently leading to pain and suffering, increased patient complaints, decreased staff satisfaction and decreased physician productivity, increased the pressure in terms of managing the hospital effectively, and poor service quality [6,7,8]. Various different studies that have been referred to earlier were focused on the patient flow system in order to study overcrowding within EDs. A patient flow system is a valuable tool for examining and evaluating hospital performance. In fact, the patients in ED usually require the utilisation of various different resources, namely beds, examining rooms, medical procedures, nurses, and physicians. This therefore suggests that the overall patient flow system may be described as a network [9]. In part, patient delays depend on how they physically flows through the network, and also on the ways in which information, equipment and other objects flow through it [10]. In actual fact, previous studies found that the problem in hospitals is that such movements throughout the patient flow network have been stopped or otherwise progress slowly owing to many different reasons. However, previous research into patient flow has assumed the ideal behaviours of patients. Owing to the technical challenges involved in modelling realistic human behaviours, existing work has considerable limitations in regard to its domain of applicability and, to some extent, on the validity of the results across a wide application spectrum. It is know that, under stressful conditions, human behaviour deviates substantially from the ideal; particularly when rules and regulations are not enforced, as found in less developed countries, such as in Libya [11,12,13]. The proposed study hypothesises that human behaviour is a key driver of overcrowding within Libyan hospitals; therefore, this paper has been focused on exploring human behaviour at a level to realistically predict a patient flow system within a critical hospital environment

2. Field study

To explore the effects of difficult patients' behaviour on the service time in the ED, Tripoli Medical Centre (TMC) was selected as the hospital for this study. TMC is one of the largest hospitals in Libya, located at the Eastern entrance of the city of Tripoli, with 1,438 beds in total. The emergency department of TMC is considered one of the most important emergency departments in the country, because it was founded to serve the residents of Tripoli, at an estimated one and a half million.

2.1. Methodology

This study has conducted telephone interviews and questionnaires with a number of doctors and nurses working within the ED at TMC; this was decided upon so that the patients' behaviour factors listed through a review of previous literature could be discussed. It is recognised that, by holding such interviews and discussion, the behaviour factors most important for delaying services within the department can be established. Telephone interviews have been conducted with group of eight nurses and four doctors. Through the telephone interviews, a series of questions that were prepared in advance were discussed. In fact, those interviews were a preliminary stage for building a questionnaire with 10 questions all about patients' behaviour within the ED. The questionnaire was distributed to all doctors (16 doctors) and nurses (20 nurses) who were working in the ED to find their opinions on the impact of the patients' behaviour on service times. The study explored issues related to patients' behaviour, such as the behaviour considered to cause weakness in the patient flow system; the effects of that behaviour on waiting time

3. Results

From the questionnaire sent to the ED staff in TMC: there were 11 doctor respondents, who represent 68.8% of the total questionnaires sent, and 14 nurses respondents, who represent 70%. The staff were asked about how long they had worked in the ED and most staff who responded (doctors and nurses) had been in their jobs over five years. Figure 1 shows the distribution of staff by years of experience.

When asked about the existence of the overcrowding in the ED, 70.5% of the doctor respondents agreed, joined by approximately eighty percent (79.7%) of the nurses. The staff were also asked to indicate whether they felt that difficult patients' behaviour issues had a negative impact on the work of their ED, and almost eighty percent (78.3%) of doctors and 80 % of nurses felt that it did. In addition, they were asked about the most important behaviour that negatively affected their ED. Table 1 shows the results of their answers.

The staff were asked to indicate the negative effects caused by the difficult patients' behaviour on the work in the TMC emergency department, and it was found that doctors (approximately 75%) and nurses (approximately 80%) agreed that the most important negative impact on the work in the ED was difficult patient behaviour, which increased patient waiting time for service. Sixty-four percent of doctors and 70% of nurses believed that unacceptable patient behaviour disturbs the patient flow system. In addition, 51.4% of doctors and 55% of nurses responded that difficult behaviour contributes of staff dissatisfaction, which negatively affects the quality of service provided (see Fig. 2).

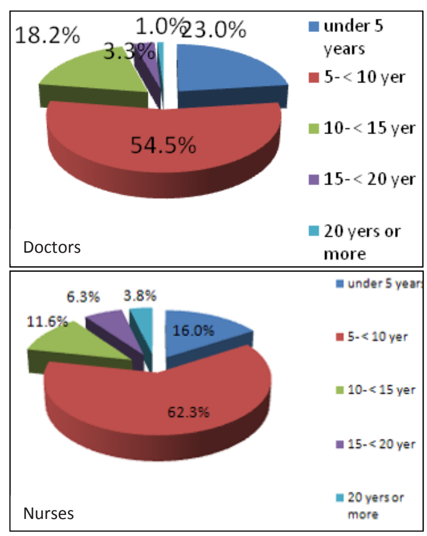

Fig. 1. Length of time staff had worked in ED

Respondents were asked for more service areas experiencing repeated unacceptable behaviour. The results show that there were six service areas experiencing delays in service because of the difficult behaviour of some patients. Table 2 shows those areas, and also shows the average real-time service, and the estimated average time that respondents believed that the difficult patient takes in addition to real service time.

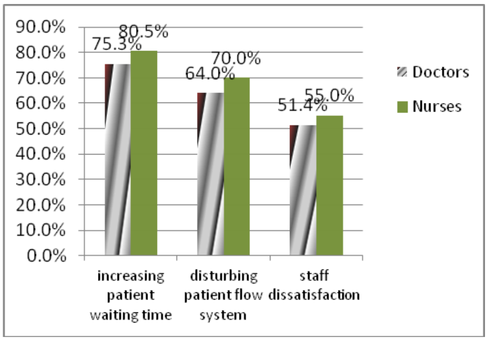

Fig. 2. The three negative effects on work at ED in TMC

Table 1. Staff opinion 0f behaviour factors affecting overcrowding

Behaviour Factors	Doctors %			Nurses %		
	M.E	Mi.E	N.E	M.E	Mi.E	N.E
Illness Believes	70.6	23	6.4	63	22.9	14.1
Over-involvement	65.3	30.1	4.6	65.8	32.1	2.1
Demanding	65.4	24.8	9.8	85.3	12.2	2.5
Arguing	62.5	27	10.5	51.8	35.8	12.4
Aggression	62	30.8	7.2	50.1	15.8	9.1
Lack of respect	58.1	27.6	14.3	75.1	34.3	15.6
Intoxication (alcoholism)	50.6	33.8	15.3	26.9	37.2	35.9
Cultural influence	30.6	40.8	28.6	59.8	30	10.2
Comm. difficulties	26.7	37.2	36.1	70.5	22.3	7.2
Interfering	22.8	46.7	30.5	35	40.6	24.4
Breaks taken	16.7	50.8	32.5	18	55.3	26.7
Where, M.E = Major effect, Mi.E = Minor effect, N.E = No Effect						

Table 2. Represents areas more exposed to the presence of unacceptable behaviour, the average real-time service, and the average estimated for the extra time caused by the behaviour of the patient

Service area	Repeated behaviour	T-1 (mins)	T-2 (mins)
Triage	• Interfering • Arguing • Communication difficulties • Illness Believes • Aggression	6	7.5
Reception	• Demanding • Aggression • Lack of respect • Cultural influence • Communication difficulties • Alcoholism	3.5	4
Exam.	• Communication difficulties • Arguing • Illness Believes	15.5	7
Diagnosis	• Interfering • Arguing	6	6
Discharge	• Cultural influence • Demanding • Demanding • Lack of respect • Over-involvement • Arguing	35	10.5
Queues	• Cultural influence • Demanding • Demanding • Lack of respect • Over-involvement • Breaks taken	60	30
Where, T-1= Mean time to provide the service T-2= Mean estimate extra time			

4. Discussion

Previous studies carried out on attempting to improve the flow of available ED resources—including physical resources (beds, equipment, etc.) and human resources (nursing staff, diagnostic staff, physician staff, etc.)—have sought to establish good solutions to the problem. In actual fact, there have been several proposed solutions for the overcrowding and length of the waiting time problem: fast-tracking is one of these proposed solutions. Fast-tracking helps to reduce patient waiting times through the mechanism of sending non-urgent patients to a specific station as opposed to waiting for emergency services with other urgent patients. Other solutions have been determined through studying queue theory, queue stricture, hospitals facilities available, and so on **[**14, 15**]**.

Despite the importance of previous studies, there has been the neglect to consider difficult patient's behaviour and its impacts on the patient flow system. Therefore, the study hypothesis has been outlined, which assumes that patient behaviours whilst waiting in a service queue is one of the reasons impeding the smooth operation of the patient flow system. To prove the hypothesis, the study relied on a survey of staff working in the ED of (TMC) to find their opinion on the issue of patients' behaviour and its impact on service.

The results show that over half of all respondents had spent more than six years working in the ED, which indicates that they have gained good experience to be able to give reliable views. Over 70% of doctors and 79% of nurses agreed that overcrowding is a significant problem in the ED at TMC. This result obviously shows the importance of conducting such a study in order to discover the reasons for this problem and work on finding a suitable solution. Doctors rated serious behaviours, shown in Table 1, which they believe to be undesirable in their emergency department, with effects on service delivery. Doctors considered illness beliefs the most important behavioural factor to cause confusion at work. This behaviour, as interpreted by the doctors surveyed, means that patients go to the ED from a belief that he/she is an emergency condition when he/she is not. According to the rules of the ED, staff cannot refuse to treat the patient who appears in the department, regardless of his/her condition; instead, staff must provide emergency services for each patient. Therefore, the illness belief behaviour leads to an increased number of patients, which causes.

5. Conclusion

This study shows that the staff who work in the ED at TMC believe that the presence of difficult behaviour of patients is a very important reason for the delay and weakening of the quality of department services delivery. It identifies the most important negative effects and service areas affected by these behaviours, as well as the staff's estimation for the extra waiting time caused by those difficult patients' behaviour. From these results, we conclude that it is necessary to find scientific and logical solutions to the problem. The most important of these solutions is the restructuring of the patient flow system to address the most common difficult behaviours within the ED.

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A new simulation-based approach to production planning and control

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Abstract. One of the most important means for manufacturing companies to succeed with increasing competition in fulfilling customers' orders is by planning and executing their activities in the most efficient way. In discrete manufacturing, production planning and control tasks lead to complex optimization problems. The paper presents a new comprehensive approach inspired from real-world manufacturing environments. The two-phase procedure starts in its first phase with local search based on fast execution-driven simulation and evaluation with multi-purpose assessment, while a detailed discrete event-driven simulation (DES) model is applied in the second phase to analyze selected solutions to controlling the stability, robustness and performance. The method can be used both for aggregate production planning and for shop floor production management in solving tasks. Efficiency can be further improved with detailed modelling of uncertainty and of various properties of production and business processes.

Keywords: simulation, performance indices, production planning and control, multi-objective optimization.

1. Introduction

In essence, production planning and control (PPC) systems deal with the allocation of limited resources to production activities in order to satisfy given customer demands over a well-defined time horizon. Both planning and control tasks lead in fact to optimization problems, in which the main goal is to create such plans that meet actual demands (constraints) and maximize production performance (i.e. profit). In practice, models of solving these optimization problems cover a very wide range due to varying characteristics of different production systems and their business environments. However, these models usually are very complex and difficult to cope with them.

One way of solving such planning problems is to use a hierarchical approach. It means that the planning process will run in a hierarchical way by ordering the corresponding decisions according to their relative importance. Hierarchical production planning uses a specific optimization model at each level of the hierarchy. Each model extends the constraints of the problem at the lower level of the hierarchy (i.e. [1], [6]).

In order to reduce complexity, production planning problems are usually solved at an aggregate level. It means that individual products (which are distinct but similar) are combined into aggregate product families that can be planned together. On the other hand, production resources (i.e. various machines or labour pools) can also be aggregated into presumable resource groups. The aggregation technique must assure that the aggregate plan can be disaggregated into feasible production (manufacturing) schedules whenever it is necessary.

Production planning process typically runs according to the rolling horizon principle. It means that a candidate plan is created for the actual time horizon and the decisions in the first few periods of the horizon are executed accordingly. Then, the candidate plan is revised and for good cause re-planned. The actual plan must be periodically revised due to the uncertainties that may occur in the demand list and in the production processes.

According to the rolling time horizon, PPC systems cover two main stages: the master planning and master scheduling are realized in the first stage, while fine or detailed scheduling and execution control is done in the second stage. The main goal of the first stage is to balance the capacity and demand. The PPC system includes the master function that produces production plans for material and capacity requirements. The second stage deals with sequencing of production orders that have already been released for production in the actual time frame. It is also decided exactly when and on which machines or workplaces the dependent jobs should be executed. The main goals of this second stage are to avoid tardiness of jobs and orders, to minimize flow times of parts, and to maximize utilization rates of machines/workplaces. For solving such detailed or fine scheduling tasks, advanced scheduling models and methods are needed. A detailed survey for the multi-objective scheduling problems is given in [5].

This paper proposes a new approach to support planning and control activities at the shop floor level of discrete manufacturing systems in a flexible, efficient and effective way. Typical problem-solving decisions include generating dependent orders, batching, resource allocation, work force assignment, task sequencing and timing issues. The main focus is set on simulation-based models used for detailed production scheduling in a discrete-parts manufacturing environment. The new, integrated fine scheduling approach is based on hierarchical and layered simulation.

2. Computer integrated application systems

Nowdays, production engineers and managers utilize more and more computer integrated application systems to support their decision making. Software systems applied to management of discrete production processes can be classified into four hierarchical groups according to the different supported fields and time horizons:

1. Enterprise Resources Planning (ERP)
2. Computer Aided Production Engineering (CAPE)
3. Manufacturing Execution Systems (MES)
4. Manufacturing Automation (MA).

This paper focuses only on the detailed scheduling method applied at shop floor production management level, i.e. as a function of the MES. However, it can similarly be used for aggregate production planning (ERP level). At the MES level, the main goal of the fine scheduler is to initiate detailed schedules that meet the master plan goals defined at the ERP level. The scheduler gets the actual data of dependent orders, products, resource environment and other technological constraints (tools, operations, buffers, and material handling issues and so on). The shop floor management defines the manufacturing goals and their priorities. Obviously, management from time to time may declare various goals. The scheduler has to provide a feasible sequence of jobs which meet the prescribed goal. As result of the scheduling process, a detailed production program is obtained, which declares the releasing sequence of jobs, and assigns all the necessary resources to them and proposes the starting time of operations. This program must not break any of the hard constraints but has to meet the predefined goals.

The computation time of the scheduling process is also an important issue that has to be taken into consideration especially when large number of internal orders, jobs, operations, resources, technological variants and constraints are involved in the problem. It is worth also mentioning again that the optimization problem, despite reducing its order at the MES level, still remains the most challenging one due to the varying characteristics of the manufacturing system over the considered time horizon as well as due to the very short time horizon available for decision making.

3. Simulation-based fine scheduling

Usually, all data of a specific manufacturing order (identifier, priority, product type, product quantity, due date, etc) are available, and can be downloaded from the ERP system database. On the other hand, all the related information on product, technology and resources (bills of materials, technological process plans, available resources, processing intensities, set-up times, etc) are available in the MES database.

The proposed fine scheduling process consists of two phases (Fig. 1). In the first phase (top layer) a wide-range fine scheduling based on deterministic data models and fast execution-simulation is used to generate several, near-optimal feasible fine schedules. In the second phase (bottom layer) a narrow-range, more precise stochastic model-based event-driven simulation is used for sharp tuning. The given set of low number candidate fine schedules is evaluated according to viewpoints of stability and behaviour in uncertain environment. That is, simulation is also performing fast and stochastic issues can also be considered. At the top layer, the focus is set on creating some near-optimal feasible schedules by considering detailed constraints and capabilities of resources, while at the bottom layer the model adjusting for various uncertainties plays the primary role.

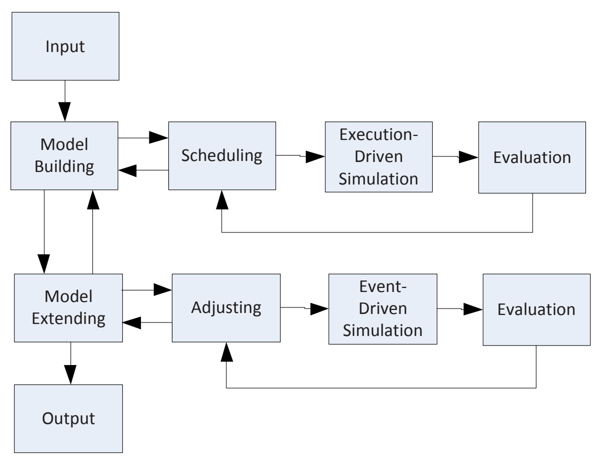

Fig. 1. Two-layered simulation-based fine scheduling.

The proposed two-phase simulation-based model supports the flexible usage of multiple production goals and requirements simultaneously. The elaborated approach helps to solve the complex, detailed scheduling problem as a whole without its decomposition. In this way, all issues like batching, assigning, sequencing and timing are answered simultaneously in much shorter time.

Moreover, simulation may easily lead to evaluation of several production performance indices already before the manufacturing execution. That may serve to corrections at MES or even at ERP level.

Based on above-mentioned two-phase modelling and simulation approach and in order to implement in practice and solve the production fine scheduling problems, special developments had to be done. To implement the first phase (top layer), a knowledge intensive searching algorithm and the corresponding software have been developed. The algorithm is based on execution-driven fast simulation, overloaded relational operators and multiple neighbouring operators. The core of the engine implemented explores iteratively the feasible solution space and creates neighbour candidate solutions by modifying the actual resource allocations, job sequences and other decision variables according to the problem space characteristics. The objective functions concerning candidate schedules are evaluated by production simulation representing the real-world environment with capacity and technological constraints. Items, parts, units and jobs are passive elements in the execution-driven simulation, and they are processed, moved, and stored by active system resources such as machines, material handling devices, humans and buffers. The numerical tracking of product units serves the time data of the manufacturing steps. The simulation process extends the pre-defined schedule to a fine schedule by calculating and assigning the time data, too. Consequently, the simulation is able to transform the original searching space to a reduced space by solving the timing sub-problem. This part of the approach encapsulates the dependency of real-world scheduling problems. Successful adaptation of the approach into practice is highly influenced by the efficiency of the simulation algorithm.

The performance analysis of the created fine schedule can be performed by calculating some objective functions based on the data of units, jobs, production orders, machines and other objects of the model. In order to express the shop floor management's goals as criteria of a multi-objective optimization problem, the software includes an evaluator module, too. This module has many such objective functions implemented, as for example:

- the number of tardy jobs;
- the sum of tardiness;
- the maximum tardiness;
- the number of set-up activities;
- the sum of set-up times;
- the average waiting rate of machines; and
- the average flow time of jobs.

It is worth mentioning here that the shop floor may be loaded with unfinished running tasks when generating schedule for the actual time horizon. So, the input data set has to include the actual state variables of the system. It means that the effects of the last confirmed schedule must be considered when creating new schedule. As described in [2, 3, 4], we have successfully applied this approach for solving extended flexible flow shop scheduling problems in practice.

However, after the first phase evaluation only very few schedule candidates have to be further analyzed, which shortens considerable the more time-consuming fine-tuning process. This is the main role of the bottom layer. Fortunately, for this purpose one may find commercial software applications available. Most of them are based on an event-driven simulation kernel, which assures flexibility and a wide spectrum of mathematical formalism in order to perform deeper analysis. The most important aspect of this analysis is related to including of uncertainty as well as of the possibility of long-term runs. The detailed event-driven simulation model captures the relevant aspects of the control problem, which cannot be represented in the deterministic execution-driven fast simulation model. The most important issues in this respect are the uncertainty of the manufacturing system, such as (for example) uncertain processing, moving and set-up times, uncertain quality and waste product rates of operations, failures or breakdowns of machines, material handling equipment and other devices. The event-driven simulator is used as a component of the scheduling system taking the role of the real production system. The control logic of the simulator ensures that the schedule must be executed according to the predefined fine schedule. The evaluation of a given candidate schedules is measured over several runs in which uncertainty can be represented by different stochastic dispersions or even by different random numbers. In addition, the commercial simulation software helps in visualization, in statistical and/or other performance evaluation and in verifying the results of the candidate fine schedules.

4. Comparison of candidate schedules

Comparing of different schedule instances regarding to different performance measures is one of the most important tasks of the evaluation of the set of feasible schedules for the same problem. In cases where two or more candidate schedules are available, one of the main tasks is to decide which is the better solution. In complex problems it is typical that different schedules can perform better according to different performance measures.

Regarding the evaluation problem at top and bottom level of the proposed approach, a mathematical model for relative comparison of individual schedules is presented in this section.

The scheduler module creates candidate schedules by systematically modifying the values of the decision variables of the initial schedule. The objective functions concerning candidate schedules are evaluated by both simulation and evaluation modules. The relational operators (i.e. "<") have been overloaded and used to compare the generated schedules according to the multiple objective functions (some examples were enumerated in the previous section). All objective functions are supposed to be given in such a form that their minimum has to be computed according to the following formula:

$$f_k : S \to \Re^+ \cup \{0\}, \forall k \in \{1,2,\cdots,K\} \quad (1)$$

Coefficients $w_k, k = 1,2,\cdots,K$ as input parameters may support the user in order to adjust the actual priority of each f_k objective function independently. Each w_k is an integer value within a pre-defined close range $w_k \in \{1,2,\cdots,W\}$ and expresses the importance of f_k.

Let $s_x, s_y \in S$ be two candidate schedule solutions. A comparison function F in order to express the relative quality of solution s_y compared to s_x as a real number was generally defined as:

$$F : S^2 \to \Re \text{ , } F(s_x, s_y) = \sum_{k=1}^{K} \left(w_k \cdot D\left(f_k(s_x), f_k(s_y)\right)\right), \qquad (2)$$

where the function D compares the schedules s_x and s_y corresponding to f_k, according to the following:

$$D : \Re^2 \to \Re \text{ , } D(a,b) = \begin{cases} 0, & \text{if } \max(a,b) = 0 \\ \dfrac{b-a}{\max(a,b)}, & \text{otherwise} \end{cases}. \qquad (3)$$

Using definition (2) the relational operators are overloaded by the following decision:

$$\left(s_x \;?\; s_y\right) := \left(F(s_x, s_y) \;?\; 0\right). \qquad (4)$$

Any of relational operators (i.e. the ones used in C++ programming: <, >, <=, >=, ==, !=) can be used between two candidate schedule solutions to compare them like two real numbers. For example, s_y is a better solution than s_x (i.e. $s_y < s_x$ is true) if $F(s_x, s_y)$ is less than zero. These definitions of the relational operators are suitable for applying them in meta-heuristics like taboo search, simulated annealing and genetic or evolutionary algorithms to solve multi-objective combinatorial optimization problems of production planning.

5. Conclusions

Production planning and control of discrete manufacturing systems becomes a complex and difficult task already for production systems of low and medium size (20-200 workplaces). The production entities (jobs and machines/workplaces), the human and technological resources, the logistical and technological constraints, the variations of operation intensities and of capacities, as well as the uncertainties of market and production demands and goals make the production planning and control decisions very difficult. Computer aided applications present scalable models at higher (ERP, MRP, SCM) hierarchical levels for helping functions of master planning and control. At lower (MES, MA) levels control decisions are model-dependent to such an extent that using of predefined or standard models is very limited. This is probably the main reason why the up-to-date commercially available MES applications still need important customized implementation, while the use of ISA-95 standard performs below the expected results.

Practical experience showed that production planning and control at MES level performs proactive, short term scheduling and reactive, on-line controlling, eventually re-planning tasks day by day. These activities can be carried out either by decisions of experienced humans, or by using of model-based decision support applications.

On the other hand, evaluation of production processes leads to multi-objective optimization problems. However, without continuous monitoring of several key performance indices (KPIs) the control of production is of lower quality of an open-loop control. Simulation models are suitable for evaluation. Based on practical experience, a two-phase hierarchical problem solving technique suits the best. In the first phase, at the top layer, creating jobs, allocating resources and filtering alternative feasible schedules has to be performed by a customized, very fast simulation model-based algorithm, which outputs only few candidate schedules. In the second phase, at the subordinated layer these schedules are evaluated more detailed and with including of stochastic or uncertain elements, which permit analysis of different variations on intensity rates, on allocations of resources, on priorities and goals. In this way, production management decisions support production results more effectively.

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Complexity in manufacturing supply chain applied to automotive industry: Modelling, analysis and a case study

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Abstract. In today's world, supply chain management becomes a key factor to achieve the goals for business. The basic principles that the organisation should take to achieve the highest potential of supply chain management, is explained in this research. The theory of "complexity" is a controversial and challenging issue for the automotive industry because this theory can be adapted to be used to solve complexity problems in the engineering field. In this project, regarding to identify and solve complexity in Toyota supply chain problem which has the inefficient process, a three dimensional complexity concept is introduced and explained to illustrate the major causes of a supply chains' complexity, which are procurement process, manufacturing system and distribution network complexity. In order to solve the complexity problems, Arena Simulation programme will be the method of this research, which is used to simulate and evaluate the existing supply chain based on the case study. After that, the proposal of improvement will be provided. Then, Katcha medel, which is an implementing model, will be given. The result comparisons indicate that Katcha system provides higher performance than the existing one in every factor including waiting time, work-in-process (WIP) and throughput time by reducing complexity of interaction of suppliers and manufacturing process and batch size. As a result, the company can achieve higher potential in order to survive in the competitive business.

Keywords: Manufacturing Supply Chain, Complexity, Simulation, Automotive Manufacturing

1. Introduction

Nowadays, business is highly competitive [1]. Every company is trying to compete better in their business by considering globalisation, customers' expectations, cost reduction, shorter allowed lead-time and shorter product life cycle [1]. In order to achieve these goals, internal and external processes must be improved [2]. Ayral [3] claims that the automotive industry is suffering from an increasing agility and flexibility in order to cope with the unpredictability and variety in customers' demand. The effects of uncertainty and unpredictability also appear at the interfaces between customers and suppliers throughout the supply chain [3]. Business management is introduced as the age of inter network competition [4]. In the last decade, the competition was brand versus brand or store versus store, but now supply chain versus supply chain or suppliers-brand-store versus suppliers-brand-store is introduced [4].

Supply Chain Management refers to the management of multiple relationships throughout the supply chain [4]. "The supply chain is not a chain of business with one-to-one, business-to-business relationships, but a network of multiple businesses and relationships" stated by Lambert and Cooper [4]. Besides, a Supply Chain is a link of materials, information and financial flows between two or more organizations [2]. Chopra and Meindl [5] also insisted that a supply chain consists of all activities including directly or indirectly activities in order to satisfy a customer requirement such as inventory, distributions, and retailers. Thus, these issues have had a considerable impact on manufacturing structures and processes which are increasing complexity level in a supply chain.

A supply chain is not a single linear process of connections, but it is a complex web-link structure [2]. Hence, major issues of complexity in a supply chain have to be identified clearly. "Complexity Theory" is an analytical method which can be used to define the problems in complicated situations [6]. Importantly, it can be adapted to solve complex problems in the "Manufacturing Supply Chain" [6]. The complexities in the automotive manufacturing supply chain attempt to deal with the manufacturing processes and links with suppliers and customers such as procurement, manufacturing and distribution issues. Validating complexity in the supply chain seems to be difficult; however, computer simulation provides a way to validate the information-theoretic model developed and to identify the impact of these problems [3].

Most engineers are always dealing with the decision-making process which usually requires understanding of the complexity in the system [7]. Modelling is a practical technique to assist decision making in order to implementing effective manufacturing systems [8]. An existing system or an implementing system can be represented by simulated model, also investigated and compared with manipulation of the system. Therefore, in manufacturing systems, simulation programmes have been widely used to illustrate the effective of incomplete decisions, such as a new schedule [3]. In this report, the Arena Simulation programme is used to identify the supply chain and performance measurement in order to optimize solutions based on a case study which is Toyota Motor Thailand Co., Ltd.

Toyota, a well-known automotive company, is the best-selling brand in Thailand [9]. The Gateway plant is considered to be one of the most famous factories because it produces and exports about an half of overall production globally. Furthermore, Toyota Motor Thailand: Gateway plant is changing continuously in their product type because of customer demands. The complexity of the supply chain is increased because it deals not only with over 13 suppliers and 300 raw materials and 14 distributors, but also faces with mixed-model assembly lines. For the case company, Arena Simulation applied on Toyota's supply chain will be a useful tool to meet customer satisfaction.

2. Complexity in automotive manufacturing supply chain

Currently, the knowledge of the components of supply chain management usually depends on experimental study; for example, in order to control a daily activity in manufacturing supply chain, companies often apply certain simple rules to deal with common problems [10]. In the real situation, many decisions are made easily by real time controlling of the supply chain activities. Obviously, the companies whose target is to raise their reactivity capacity that assists to solve problems by reducing complexity level. Mostly, the problems are eliminated by reducing its complexity [10].

Nevertheless, from the over view, the highly complex and unsolved problems are still existing because extraordinarily complex issues cannot be solved [10]. For instance, the firms cannot predict exactly the number of inventories alone in supply chain. There are many causes of dysfunction, which are production and distribution flexibility, delivery time reduction, total quality control, new investments, have already overwhelmed the limit of its efficiency [10].

In automotive manufacturing supply chain, complexity implies the number of elements of sub-systems, level of connectivity and interaction among the elements, unpredictability, unstability, and variety in product and system states. However, the "Complexity Theory" can be applied to identify complexity of manufacturing supply chain [6]. As Gottinger [11] claimed "the more we are able to describe the complexity of an objective, the more we are able to learn about the objective". Likewise, the understanding of system's complexity is the first phrase to solve the problems in the system [12].

Mostly, automotive industries obtain raw materials from many different suppliers and sell products to many different customers; hence, each product type has a different supply chain as Waters [13] stated "Every product has its own unique supply chain which can be both complicated and long sequence".

The complexities in the automotive industry supply chain usually attempt to deal with many sources of complexity such as network complexity, manufacturing complexity, product range complexity, customer complexity, procurement complexity, organisational complexity, information complexity and distribution complexity. Wisner [14] defined 3 foundation elements of complexity in a supply chain, which are "Purchasing", "Operations" and "Distribution" complexity as shown in Fig.1. These complexities can be examined in followings:

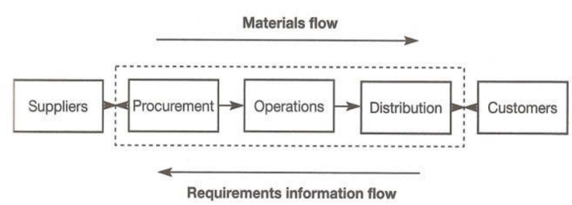

Fig. 1. Complexity in an automotive manufacturing supply chain [13]

2.1. Procurement complexity

Procurement, which is a process between manufacturer and supplier (Upstream activities), is the key link between the company and its suppliers to make sure that firms get "the right material, from the right suppliers, in the right quantity, in the right place, at the right time, with the right quality" [15]. This difficulty can be separated into three topics:

1) Number of Suppliers and Level of Its Interaction

Kauffman [16], Waldrop [17] and Dooley [18] insisted that supplier complexity bases on a factor of the number of suppliers in the supply chain and the level of supplier interaction. The complexity level of the supply base is a critical factor for the level of transaction cost, the risk of supply base and the respond of the suppliers [19].

Mostly, suppliers have their own suppliers called sub-suppliers who provide small components to the suppliers [20]. If a sub-supplier cannot delivery raw material on time, the supplier cannot operate and delivery the component on time. As a result, the company is not able to respond to customer demand [13]. This issue is a combination complexity which occurs when the system range changes with time which is changing suppliers' demand [6].

2) Differentiation of suppliers

In the supply base, differentiation of suppliers can be resulted in the level of different characteristics, which exist in the supply base, such as technical capability (e.g. Supplier does not have enough knowledge or specific tool to manufacture the raw materials), operational practices (e.g. One supplier manufactures in a push system, but another supplier manufactures in a pull system), Cross-border barriers (e.g. They are speaking in different languages, or the raw materials have to travel a long distance) [19].

3) Non-standard raw materials

A distinction can be made between standard product raw material and nonstandard raw materials. Standard raw materials are defined as materials which do not specify suppliers [20]. Typically, they are the availability of several sources of supply which enlarges the possibilities in the source selection process. For non-standard raw material, the company, who buys the raw material, is forced to obtain these parts from one supplier only [20]. Non-standard raw material is an imaginary complexity which has to be eliminated [6].

4) Raw material variety

These days, customer requires more and more customized goods, which means a high number of varied products has to be provided [21]. Therefore, complex and wide product structures are consisted of a numerous number of components [21].

Vaart [20] stated that a large variety of products will result in a lower predictable demand on the level of production types. A vast range of products means that the average demand per variant is low. Hence, the difficulty of forecasting at the individual variant level builds up as a result of forecast error [1]. Consequently, the complexity as experienced by the procurement system is related to the number of product families. However, in order to decrease real complexity, the products have to be various to achieve functional requirement which is customer demand [6].

5) Order process

Once the order is made, it needs to spend a time for waiting the actual orders. Besides, the manufacturer always takes a consideration on the order priorities to create a procurement schedule [20]. However, there is a delay for waiting the orders to be converted into the lists due to checking and allocation process. Moreover, in just-in-time method, suppliers sometimes get notice only 8 to 10 hours before "final call-off" [15]. This issue is a combination complexity which occurs when the system range changes with time which is changing the orders from the manufacturer [16].

2.2. Manufacturing complexity

This complexity is an internal procedure in firms (Internal Supply Chain). At this process, the main complexity in industrial manufacturing is needed to be considered in many aspects, which can be divided into three components as shown below:

1) Multiple operation

In the manufacturing process, lengthy processes including many different activities will not only extend lead times, but also increase unsteadiness in performance of the system [1]. The expanding steps in a process will increase the complexity in the system, and the greater possibility that there will be frequent discrepancies between planned and actual outcomes [1]. This difficulty is an imaginary complexity which should be identified and eliminated.

2) Product variety

A numerous variety in components and assemblies needs a precise responding in term of production planning and control [22] and [23]. Besides, due to the changing of production orders, the manufacturing process increases its complexity [21]. This affects to expanding cycle time and lead time, consequently [21].

This complexity has been defined in an analytical form for manufacturing systems as a measure of how product variety complicates the process; for instance, mixed-model assembly line [24] (See Fig.2). This assembly line may cause longer lead-time due to difference operation time in each model [24]. Hu [24] stated "The high number of variety undoubtedly presents enormous difficulties in the design and operation of the assembly systems and supply chain". For example, Toyota Company Thailand: Gateway Plant is producing five types of cars, and there are around 10 colours in each type. The manufacturers face with a combination complexity which occurs when the system range changes with time which is various products. However, in order to achieve customer demand, the products need to be various which can reduce real complexity in the system [6].

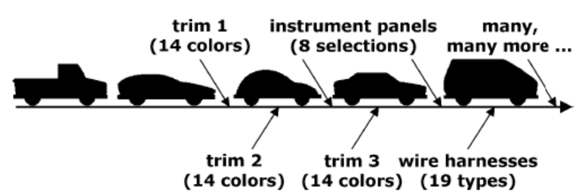

Fig. 2. Automobile mixed-model assembly line [24]

3) Lack of Employees' Knowledge

Knowledge is particularly crucial for firms with can lead and conduct the employees to achieve the works easily and accurately. Without knowledge, worker cannot assemble a simple product or even use a machine [25].

Suh [6] stated that when lack of employees' knowledge occurs, imaginary complexity will be happened.

4) Production Planning and Control

This issue deals with customers' demand undifferentiated flexibility [15]. Lauff and Werner [11] addressed "The complexity of scheduling problems in dealing with variety and uncertainty. Uncertainty comes not only from the customer, but also from the shop floor control which is production planning and control". "The disturbances and the complexity of scheduling cause deviations from a plan that is often overoptimistic" stated by Stoop and Wiers [12]. This issue is a combination complexity which occurs when the system range changes with time which is changing volume and variety of products [6].

2.3. Distribution complexity

Distribution is a process between customer and retailer (Upstream activities), is the key link between the company and its distributors to make sure that their customers receive products on time [16]. This complexity can be separated into three issues:

1) Delivery Time

Timeline and consistency of delivery is requested by customers [26]. The company has to deliver products on time in order to satisfy the customers. Moreover, some customer need higher service levels and greater product availability; for example, they want the product to be posted and delivered within 24 hours. Hence, it is exceedingly difficult to forecast the demands. This problem is a combination complexity which occurs when the system range changes with time which is changing of customer demand [6].

2) Inventory Level

Demand changes are affecting directly to usual behaviour in the supply chain such as a decreasing or increasing in demand. Many manufacturers end up with the highly inventory cost with their products in warehouses because they do not link to the actual demand from customers via retailers or dealers [26]. They should reduce its level of inventories maintaining the same level of service or increasing the level of service [26]. This issue is an imagine complexity which occurs because lack of understanding about customer demand [6].

3. Development of modeling and simulation

3.1. Data for model building

The specified data will be collected in order to transform the existing system data into the simulation model. The data for modeling building can be divided into 2 steps which are experimental & key performance factors and input parameters. These steps will be explained in the paragraph below:

Experimental factors

All the input factors are experimental factors. These factors would be changed in the implementing system to improve the performance of the existing system and complete the objectives.

1) Lot Size of Production

The number of lot size could be decreased which means a number per arrival will be reduced.

2) Schedule of Part Arrival

After the lot size is reduced, the overall quantity should be maintained by increasing the number of lots.

3) Manufacturing Quantity

The manufacturing quantity should be calculated by customer demands in order to reduce inventory and work-in-process.

Key performance factors

After the model is created completely, the key performance factors should be defined in order to demonstrate the system performance, analyse, compare and make decisions. These factors will be examined in the following:

1) Waiting time

Waiting time shows the bottle-neck of the system which should be eliminated by increasing resources or improving efficiency of the process. This factor should be reduced in order to minimise throughput time.

2) Queuing number

According to waiting time, the number of the queue will increase when the products are waiting in front of production line or somewhere in supply chain.

3) Work-in-process (WIP)

Askin and Standridge (1993) stated "Work-in-process is the number of partially completed units in processing at any given time". When the number of WIP is high, it may cause delay of delivery.

4) Throughput time

Throughput time should be as low as possible in order to quickly responding customer demands. "Throughput time composes of the processing time, set up time, move (material handling) time and plus wait time" noted by Askin and Standridge [27].

3.2. Modeling building

In this research, ARENA Simulation (version 13.5) is used to build a simulation of the supply chain model based on Toyota Company in Thailand –a case study. There are four main steps that need to be achieved. Those steps are problem analysis, modeling and testing, experimentation and analysis and Implementation as shown in Fig.3. and Fig.4.

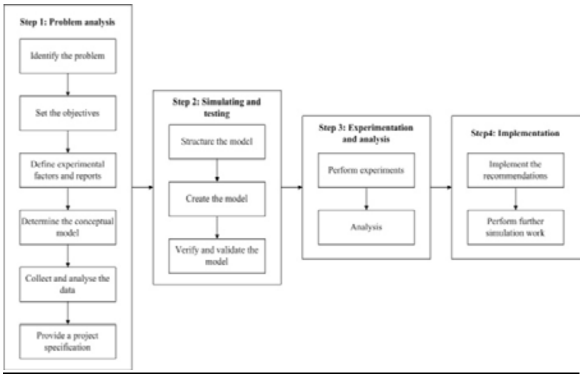

Fig.3. Step of modeling and simulation [28]

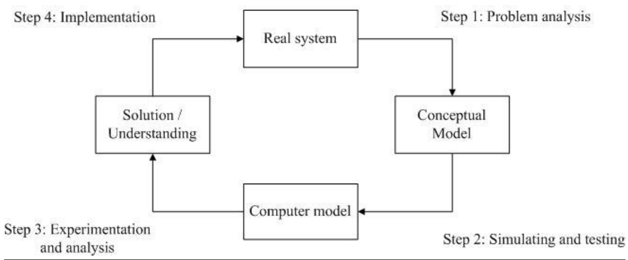

Fig.4. Modeling process [10]

The structural model is significant for the modeler before creating the model, which including the defining elements and the data logically, because it helps users understanding clearly with the system. The layout diagram of Toyota supply chain system for the simulation model is illustrated in Fig.5. The diagram indicates the raw materials are being moved from the suppliers to the manufacturing process, and delivered to distributors and the end-customer.

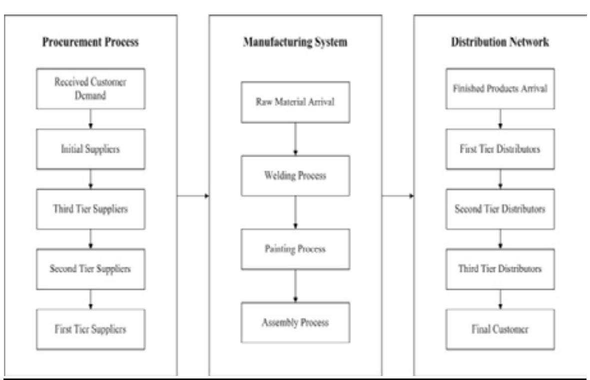

Fig. 5. Layout diagram of Toyota supply chain system

3.3. Arena simulation model

This section shows coding process for modelling the supply chain system in Toyota Company, which is translated by Arena Simulation programme (version 13.5). The model will be built logically according to the layout diagram. The completed model is divided into 3 main processes as shown in Appendix 1, Appendix 2 and Appendix 3.

4. A case study

4.1. Comparison of toyota procurement process results

Fig.6 illustrates the waiting time of components comparison in Toyota procurement process. The waiting times of all components throughout the existing system are extremely high, which are more than 45 minutes in each component. On the other hand, the waiting times of all components in Katcha system are around 20 minutes in each component.

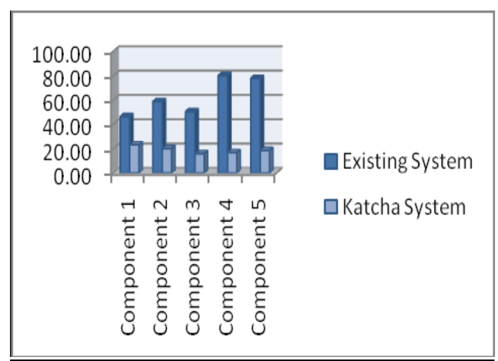

Fig. 6. Toyota procurement process waiting time of the components comparisons

According to applying the proposal improvement (See Table 1), the waiting times of Katcha procurement process are reduced dramatically in all components due to reducing batch size from 6 to 3 per batch and decreasing complexity of interaction suppliers. Consequently, the waiting times of all components in Katcha system are mostly halved comparing with existing system; for example, the waiting time of component 4 in existing is higher than the waiting time in Katcha system by 63 minutes or about 80 percentages.

Table 1. Proposal Improvement of the Katcha system

		Existing System	Katcha System
Procurement Process	Number of Suppliers	13	20
	Batch Size	6	3
Manufacturing System	Number of Welding Process	12	15
Distribution Network	Inventory Level (Parts)	25	15

Fig. 7 shows the waiting time of the processes comparisons in Toyota procurement process. Importantly, the waiting times of all processes in the actual system are higher than the waiting times of all processes in the proposed system.

After apply the proposal into the system, the waiting time in the processes are decreased dramatically. For instance, adding one more supplier to produce component 3 and 4 in the first tier supplier section, separately. Thus, the waiting times of component 3 and 4 in the first tier supplier are considerably dropped by almost 80 percents. Moreover, the total waiting time of the processes in Toyota procurement system is reduced by about 148 minutes or 75 percents.

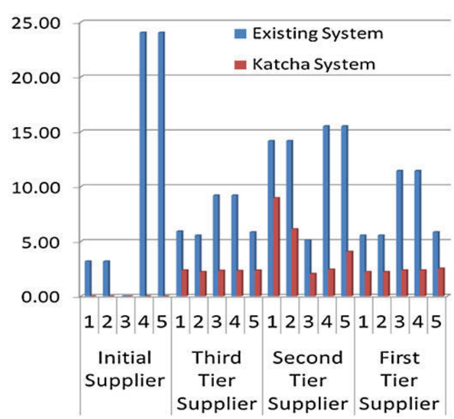

Fig. 7. Toyota procurement process waiting time in the processes comparisons

Fig. 8 demonstrates the work-in-process (WIP) comparisons in Toyota procurement process. Obviously, the numbers of work-in-process (WIP) of all components in the existing system are higher than the work-in-process (WIP) in the proposed system.

In the proposed system, the numbers of work-in-process (WIP) of the components are decreased significantly because of reducing batch size by 3 to 3 per batch and eliminating complexity by removing the bottle necks. The numbers of work-in-process (WIP) are dropped considerably compared with the actual system. For instance, there is a noticeable decrease in the number of work-in-process (WIP) of component 4 by approximately 13 parts or 70 percents.

According to the numbers of work-in-process (WIP) of the components, the performance factor of the actual system has been improved by decreasing the total number of work-in-process (WIP) in the procurement process by 44 components or 60.66 percents.

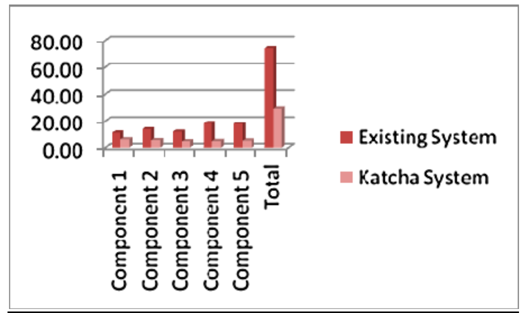

Fig. 8. Toyota procurement process work-in-process (WIP) comparisons

Fig. 9 illustrates the throughput time comparisons in Toyota procurement system. The average throughput time of the components in the existing system is higher than the Katcha system.

After applying the proposal improvement, the level of the average throughput is decreased significantly; for example, there is a noticeable drop in the throughput time of component 4 from about 90 minutes to around 26 minutes. As a result, in term of throughput time, the Katcha system provides a better performance factor by reducing the total throughput time in Toyota procurement system by approximately 220 minutes or 60 percents.

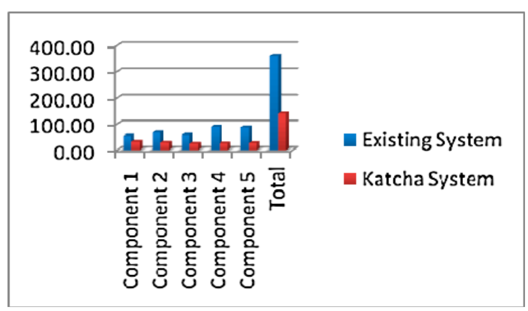

Fig. 9. Toyota procurement process throughput time comparisons

4.2. Comparison of toyota manufacturing system results

As shown in Fig.10, the waiting times of products in existing manufacturing system in Toyota Company are significantly higher than the waiting times of products in the Katcha system. For instance, the number of waiting of Camry products is plummeted from 0.185 minutes to 0.029 minutes.

As a result, the proposed system improves the performance of the actual system in term of waiting time of products by reducing the total waiting time by about 60 percents.

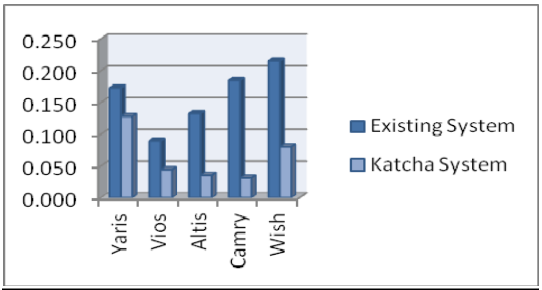

Fig. 10. Toyota manufacturing system waiting time of the products comparisons

Table 2 illustrates the waiting time of the manufacturing comparisons in Toyota procurement process. Overall, the waiting times of every process in the actual system are higher than the waiting times of all processes in the proposed system. In the existing system, the complexity that causes high waiting time of the processes is multiple operations. This complexity affects the potential of the system by producing bottle necks in the process. However, the proposal of improvement has been applied to the system, which is adding more station in the interaction processes in order to reduce complexity of the system by distribution work load.

As a result, the proposed system increases the performance of the system by reducing the total waiting time of the processes in Toyota manufacturing system by more than 70 percents (See Table 1.).

Table 2. Toyota manufacturing system waiting time in the processes comparisons

		Existing System (Minutes)	Implementing System (Minutes)	% Difference
Yaris Welding Process	1	0.0218	0	-
	2	0.0248	0.0022	-
	3	0.0967	0.0957	-
Vios Welding Process	1	0.0218	0	-
	2	0.0320	0.0074	-77.00
	3	0.0060	0.0064	7.61
Altis Welding Process	1	0.0031	0.0032	2.66
	2	0.0452	0	-
	3	0.0560	0.0023	-95.95
Camry Welding Process	1	0.0397	0	-
	2	0.0452	0	-
	3	0.0706	0.0006	-99.17
Wish Welding Process	1	0.0397	0	-
	2	0.0862	0.0011	-98.73
	3	0.0554	0.0468	-15.62
Painting Process	1	0.0263	0.0269	2.49
	2	0.0022	0.0022	2.94
	3	0.0005	0.0005	2.20
Assembly Process	1	0.0002	0.0002	-1.87
	2	0.0003	0.0003	-3.80
	3	0.0001	0.0001	-0.07
Total		0.674	0.196	-70.92

Fig.11 presents the work-in-process (WIP) comparisons in Toyota manufacturing process. The numbers of work-in-process (WIP) of all components in the proposed system are slightly lower than the work-in-process (WIP) in the existing system.

According to adding more processes in the system, the complexity, which are the bottle necks, are eliminated. As a result, the performance factor of the actual system, which is work-in-process (WIP), has been improved by reducing the total number of work-in-process (WIP) in the manufacturing system by approximately 11 percents.

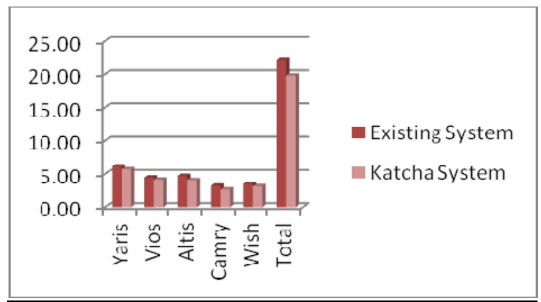

Fig. 11. Toyota manufacturing system work-in-process (WIP) comparisons

Fig.12. demonstrates the total time comparisons in Toyota manufacturing system. The average throughput time of the components in the existing system is slightly higher than the Katcha system.

The actual system has been improved in many ways such as reducing waiting time of components and in processes and decreasing the number of work-in-process (WIP) by reducing and eliminating the complexity in the system. Therefore, in term of throughput time, the proposed system improves the performance factor by reducing the total throughput time in Toyota manufacturing system by approximately 13 percents.

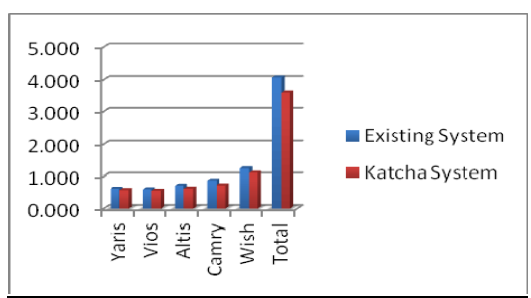

Fig. 12. Toyota manufacturing system throughput time comparisons

4.3. Comparison of toyota distribution network results

Table 3 illustrates the waiting time of the processes in Toyota distribution network. Obviously, all of the waiting times in the existing process are significantly higher than the proposed ones.

In the actual system, the complexity that causes high waiting time of the processes is the high level of inventory. This complexity affects the performance of the system by increasing waiting time. Nevertheless, the applying of the proposal improvement reduces complexity in the distribution system by decreasing the inventories. As a result, the total waiting time of the processes in Toyota distribution network is dropped noticeably by more than 55 percents (See Table 3).

Table 3. Toyota distribution network waiting time in the processes comparisons

Inventory		Existing System (Minutes)	Implementing System (Minutes)	% Difference
First Tier Distributor	1	46.89	27.75	-40.81
	2	46.39	27.26	-41.24
Second Tier Distributor	1	63.08	28.26	-55.20
	2	65.00	28.00	-56.92
	3	60.72	26.16	-56.92
	4	68.46	28.64	-58.17
Third Tier Distributor	1	69.57	29.77	-57.21
	2	72.90	32.82	-54.97
	3	75.02	29.07	-61.25
	4	68.75	30.77	-55.24
	5	64.57	28.95	-55.16
	6	68.75	26.30	-61.74
	7	72.18	33.61	-53.44
	8	76.98	30.78	-60.01
Total		919.24	408.14	-55.60

Fig. 13 illustrates the work-in-process (WIP) comparisons in Toyota distribution network. Importantly, the number of work-in-process (WIP) in all products of the actual system is higher than the work-in-process (WIP) in the Katcha system. In addition, the performance factor of the actual system has been improved by decreasing the total number of work-in-process (WIP) in the procurement process by 49 parts or about 53 percents.

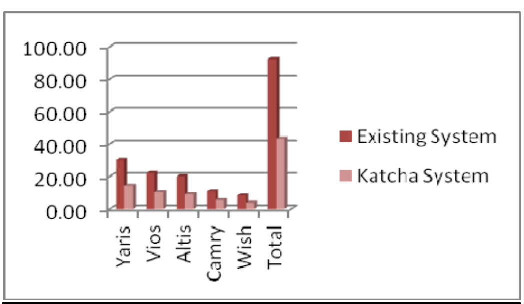

Fig. 13 Toyota distribution network work-in-process (WIP) comparisons

Fig.14 illustrates the throughput time comparisons in Toyota distribution network system. The average throughput time of the components in the actual system is considerably higher than Katcha system.

The actual system has been improved by the proposal of improvement in term of reducing waiting time of products and decreasing the number of work-in-process (WIP) by decreasing and eliminating the complexity in the system. Thus, the average throughput is declined significantly. There is a considerable drop in the throughput time of Wish products from about 180 minutes to approximately 83 minutes.

As a result, in term of throughput time, Katcha system gives a better performance factor by reducing the total throughput time in Toyota distribution network by approximately 475 minutes or 53 percents.

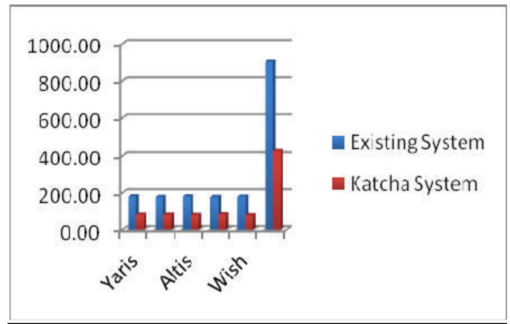

Fig. 14. Toyota distribution network throughput time comparisons

5. Discussions

Supplier complexity is based on a factor of the number of suppliers in the supply chain system. Hence, the number of suppliers in the system should be reduced to be a minimum number in order to minimize the complexity in the supplier process. However, in this case, there are 13 suppliers throughout the procurement process, but the number of suppliers should be increased to be 20 suppliers because there are some bottlenecks, which are increasing lead time and queuing in the process.

The level of supplier interaction is one of the crucial complexities in the supply chain, which must be reduced. In the procurement process, the status of interaction between suppliers is extremely high due to the link between components. To solve this complexity, decentralization suppliers have been applied throughout the Toyota procurement system. Therefore, each supplier in each state will produce only a process for only one component.

Batch size reduction is a useful technique to leveling of supplier process. Large batch size causes an increasing of the number of queuing, work-in-process (WIP), throughput time in the procurement process; hence, batch size in each supplier must be reduced to be minimum.

In manufacturing system, lengthy processes with many different activities will increase total time and unsteadiness in performance of the system. Thus, the processes in the manufacturing system should be shortened in order to decrease throughput time of the system. Moreover, the interaction processes, which are the processes that operate for two or more different products, should be separated. In this situation, there are some interactions in the processes, which should be reduced. Thus, a number of processes will be added into the system in order to distribute the work load and reduce complexity in the system.

Mixed-model assembly line may cause longer lead time due to difference operation time in each model because the high number of variety causes complexity in the production system. Therefore, the variety of the products should be reduced in order to decrease the complexity in the system. Nonetheless, in fact, the product variety is very important for sales, which provide profits for the company by responding customer needs; hence, the variety of products cannot be reduced. Then, the solution is to improve the efficiency of the system by eliminating the wastes instead.

Due to the fluctuating of the customer demand, the company ends up with high inventory with their products in warehouses. The high level of inventory is a crucial complexity in Toyota distribution network because it increases extremely costs for the company to hold the inventory; therefore, the links between customers and manufacturer should be clearly defined, and the company should reduce the level of inventories with maintaining the same level of service. In this case, there are some high levels of inventory in the distribution network, which should be reduced. Hence, the level of inventories is decreased throughout the system.

The result comparisons indicate that Katcha system provides higher performance than the existing one in every factor including waiting time, work-in-process (WIP) and throughput time. The total waiting time is reduced about 70 percents in the procurement process, 60 percents in the manufacturing system and 55 percents in the distribution network. The total number of work-in-process (WIP) is dropped about 61, 11 and 53 percents in the procurement process, the manufacturing system and the distribution network, respectively. The total throughput time is declined approximately 61 percents in the procurement process, 12 percents in the manufacturing system and 53 percents in the distribution network. As a result, if Toyota Company applies the proposal of improvement to its supply chain, the supply chain system will obtain greater performance.

6. Conclusions

The main objective of supply chain management is to respond customer need by delivery on time with low cost and high quality. It is very important for Toyota Company to identify and evaluate its supply chain clearly in order to achieve the objective. Mixed-model assembly system, which brings many benefits such as saving investment cost by sharing resources in the same production line and absorbing demand fluctuation, has been used in Toyota Company: Gateway plant. However, the high number of interaction between suppliers, system integration and product variety including mixed-model assembly system increase the complexity of Toyota supply chain system. Hence, simulation techniques are playing an important role to evaluate and simulate the complexity in the supply chain.

In this research, Arena simulation programme is used for modeling the existing supply chain. After the proposal of improvement is proposed, an implementing system called Katcha system will be simulated. The supply chain system in Toyota Company can be divided into 3 sections, which are procurement process, manufacturing system and distribution network. The key performance factors of simulated results are compared between the actual supply chain system and the proposed supply chain system.

In conclusion, an effective supply chain can be achieved by consideration of all complexities in the system. In order to reduce or eliminate them, the simulation should be used to evaluate and improve the supply chain system. This would lead to several improvements for responding to the customer needs and the success of the company to survive in the competitive business.

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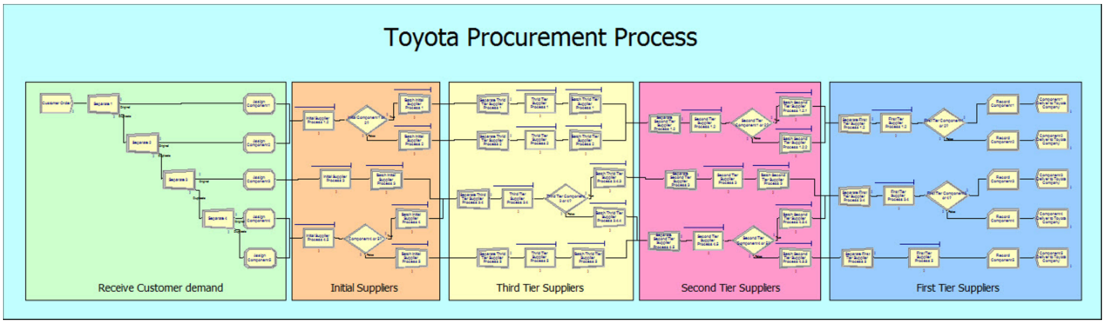
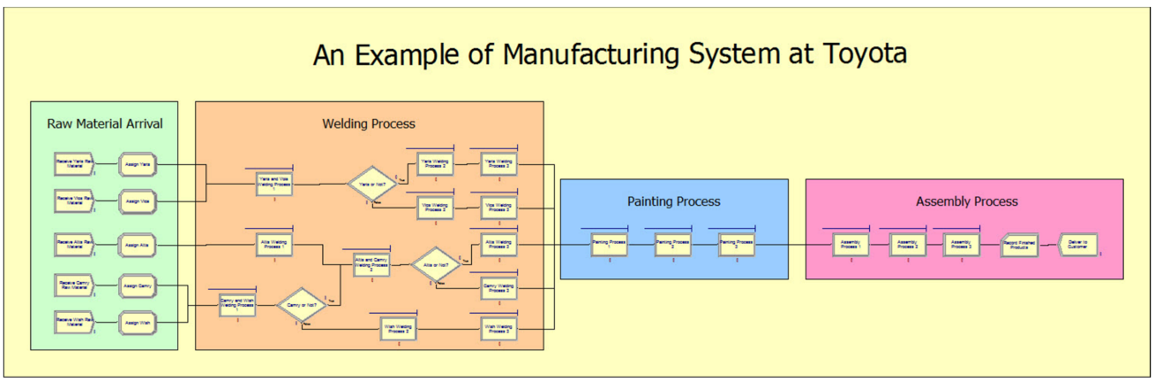
Appendices

Appendix 1. Flow chart of the existing Toyota procurement process model



Appendix 2. Flow chart of the existing Toyota manufacturing system model



Appendix 3. Flow chart of the existing Toyota distribution network model