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Operations Research is the application of the methods of science to complex problems arising in the direction and management of large systems of men, machines, materials and money in industry, business government and defence. The distinctive approach is to develop a scientific model of the system, incorporating measurements of factors such as chance and risk, with which to predict and compare the outcomes of alternative decisions, strategies or controls. The purpose is to help management determine its policy and actions scientifically.

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Guest Editorial

The 20th National Conference of Australian Society for Operations Research incorporating the 5th International Intelligent Logistics System Conference was held on the Gold Coast, Australia, in September 2009. It is our honour, on behalf of the Australian Society for Operations Research to present these special post-conference issues, which provide a unique opportunity to maintain currency with Operations Research issues in Australia and other parts of the world. An encouraging feature of the papers is the breadth they cover in both theory and application. These special issues contain a range of papers dealing with different areas relating to the theme of the conference "Making the Future better by Operations Research". The majority of them deal with application and analysis. Some of the papers are theoretical and discuss the techniques required to analyse real life applications. As a result, the topics covered in these papers highlight the diversity of the applications of Operations Research techniques.

In this issue, Groen and Selvadurai study the strategic positioning of tsunami detection buoys in the Caribbean. The paper proposes a model for determining the strategic locations for the minimum number of Deep-ocean Assessment and Reporting of Tsunami (DART) buoy. Hidayat, Takahashi, Morikawa, Hamada, Diawati and Cakravastia investigate supply chain strategies and introduce the strategy Mixed Component Commonality (MCC). Stanton and Rees explore the application of the System Intervention Methodology and the System Instantiation Comparison Method in the evaluation of defence options. Toth, Wagenitz and Klingebiel study dynamic supply chain planning and introduce RFID-based Logistic Assistance System as a new software paradigm. Cao, Coutts and Pietsch investigate defence future vehicle options and develop a ranking and selection procedure.

The editors of the special issues wish to express their appreciation to all authors for the contribution of their latest findings to Operations Research. We would also like to thank the reviewers for the involvement of the reviewing process in ensuring the maintenance of the highest scientific standards for these special issues. The reader is reminded that the contents prepared by the author were electronically reproduced for publication. Therefore, the views and opinions are those of the authors. Anyone with questions about a paper should contact the authors.

Guest Editors
Erhan Kozan and Andy Wong

A Recognition for ASOR Bulletin

ASOR Bulletin has recently been recognised as a refereed journal and upgraded it from unranked to 'C' journal in the latest 2010 ERA listing prepared by the Australian Research Council (ARC). See the details below with the field of research codes. Note that APJOR and ITOR are also ranked as 'C' in 2010 ERA. I like to thank all the editorial board members, our reviewers, and web editor for their advice /suggestion and effort in achieving such a wonderful recognition.

Ruhul Sarker
Editor-in-Chief
ASOR Bulletin

Journals on 2010 final list with

ERA Journal ID	Ranking	Title	ISSN
		Field of Research: 0806 Information Systems	
41356	C	ASOR Bulletin	0812-860X 1446-6678
		Field of Research: 1503 Business and Management	
41356	C	ASOR Bulletin	0812-860X 1446-6678

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Dynamic Supply Chain Planning with Logistic Assistant Systems

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Abstract

Considering new challenges in global markets, companies are forced to plan their supply chains relating to more flexibility, effectiveness and cost reduction. Today, Advanced Planning Systems (APS) are applied to manage availability of supply goods (available/capable to promise ATP/CTP) and to smooth inventory levels due to fluctuating demands and insecure market forecasts. High value added branches, like the automotive industry, are characterized by complex, often sales-based product configurations resulting in literally millions of possible product variants. Furthermore, a high percentage of value creation is done by global supply networks with high order lead times, dynamic and risky transport relations and high transfer stocks. Today, the necessity of global ATP taking dynamic supply network behaviour and collaborative partnerships into account is not covered by the given APS-Software. This paper will introduce Logistic Assistant Systems (LAS) as a new generation of SCM-Software, which allows dynamic and collaborative supply chain planning by providing APS like functionalities with a simulation based approach. The developed simulation component is able to handle the complexity of high value added branches with efficient algorithms, to forecast the supply chain behaviour (future stock range monitoring, dynamic ATP and resulting costs) taking different scenarios into account. It has been demonstrated to produce convincing results, e.g. in projects with Volkswagen AG.

Keywords: Dynamic Supply Chain Planning, Logistic Assistant Systems

Introduction

Order management predominantly encompasses planning, controlling and monitoring of customer orders and their related production, supply, and distribution orders. Thus, order management forms an interface between a manufacturing enterprise and its distribution channels, suppliers, resellers and customers (Laakmann et al. 2003). Nevertheless, today's supply chains are characterized by complex, global supply networks with long order lead times, dynamic, instable transport relations and high transfer stocks.

Thus effective order management depends on the availability and interpretation of key figures. In the last year we notice significant progress considering the availability of these figures; not least due to the continuing establishment of data warehouses.

In general, data warehouses are nothing more than databases which consolidate data (transaction data, inventories, etc.) originating from different systems for reporting purposes (Single Point of Truth). This data is updated regularly and periodically (daily, weekly, etc.) and every interested party may access this data nowadays as performance issues are not a problem anymore. Analysis functionalities comprise of development of transfer stocks, inventories and lead times taking into account numerous criteria. So, operative decisions obtain a valid base.

The deployment of RFID technology is supposed to further enhance the quality of supply chain data. Yet, not all technological questions in context of RFID have been answered today.

Assuming that research and industry is capable to overcome these problems: To tap the full potential of RFID technology some inevitable steps may be identified.

The collected data from RFID gates needs to be consolidated, connected to the business context and made available to all interested parties. One could state that the integration of this data into given data warehouses is essential.

But to use this information for controlling purposes, a continuous update of this data is necessary. A data warehouse analysis which is indicating a supply chain problem has already missed the point in time where a reaction would have been optimal. This lack of actuality is overcome by the comparatively new technology of Complex Event Processing (CEP) (Eckert and Bry 2009).

CEP systems control time critical processes continuously and in real-time, thus supporting the analysis and interpretation of supply chain events and their chronology. To realize this, a CEP system subscribes to data flows from different systems in order to aggregate and interpret data, taking into account the chronological and causal connection. CEP systems offer a specific query language called CPL (Continuous Query Language). CPL broadens the given and proven concepts of SQL (Structured Query Language) by functionalities for temporal analysis.

With CEP it is possible to analyse logistical systems in their development over time. This is obviously advancement over state-of-the-art business warehouses. But there is still a large semantic gap between the concepts of a more or less general purpose query language (focus on bits and bytes) and the information a logistician would like to derive from the data at hand. A typical question is for example: Will there be a stockout situation in the next few weeks given the current order forecasts? The focus is on (fore-casted) orders, parts and specific business processes that influence the stock situation in the time interval looked at.

Though RFID and CEP offer a promising technological background, from the viewpoint of logistics in general and global order management in special, we identify three significant areas requiring further research.

First, the major challenge in the next three to five years for logistics will be the advancing need for dynamism. This strategic change is characterized by rapid dissemination of new technologies, new and often aggressive competitors, a tightening integration of material and finance flow, a parallel fragmentation and dynamic reconfiguration of logistics networks. So we plead for an adaptive, task-oriented view on logistics (Klingebiel 2009). The technological implications will be explicated in the next chapter.

Second, to establish RFID-based, effective, global order management all supply chain partners have to define and follow joint objectives, share proprietary data and process information and trust each other. Often a lack of trust between the different actors avoids successful supply chain collaboration (Barratt 2004; Ireland and Bruce 2000). To face this problem, it is necessary to involve all relevant actors along the supply chain for defining a collaborative process and show the benefits for all partners (Dudek and Stadtler 2004). To implement a manageable process, information technology is an essential enabler for a collaborative relationship across the supply chain (Mentzer et al. 2000).

Third, to support collaborative planning, control and decision processes in complex global multimodal supply chains, network partners have to apply logistic concepts which are fully supported by IT systems. Those software applications have to consolidate all relevant information along the supply chain and provide it to the responsible experts and planners. The setup of accountabilities in the network and the way information is processed can only be determined individually for each supply network, according to the requirements of the given process and respective logistics concept.

Chapter three of this paper will explain the concept of RFID-based Logistic Assistance Systems (RFID-LAS) which runs against these two challenges while incarnating a task-oriented approach. Chapter four will introduce a prototype and chapter five will conclude with the perspective for RFID-based LAS.

Adaptivity and Task-Oriented Logistics as Major Logistics Challenge

The major challenge in the next three to five years for logistics will be the advancing need for dynamism. This strategic change is characterized by rapid dissemination of new technologies, new and often aggressive competitors, a tightening integration of material and finance flow, a parallel fragmentation and dynamic reconfiguration of logistics networks (Nyhuis 2008).

Increasing external product variety and accelerating innovation speed – especially regarding product complexity, product configuration and shortened product life cycles – are symptoms of these trends. (Rinza 2007). Wherein Original Equipment Manufacturers (OEMs) are not isolated, every producing enterprise is embedded in several supply networks. Here a multitude of producers, suppliers and logistics service providers team up towards the final product for the customer.

One may state that with this background today's logistics networks are designed to be flexible. They can handle a bandwidth of system loads and turbulence. Yet although several options and variations have been taken into account within the design phase, the final logistics structures and processes have been, long term wise, and aligned towards a certain range of turbulence. But the by definition out-dated planning assumptions imply a permanent exceedance of flexibility constraints. High and especially even short-term incalculable logistics costs result (Kreuzer et al. 2008).

Consequently most enterprises have realized that dynamism reaches a new dimension which current flexibility specifications do not satisfy. The inflicted costs are no longer economically justifiable. The resulting requirements cannot be met by logistical structures and processes which are preferably adjusted to temporarily static circumstances. This environmental dynamism can only be counteracted by a dynamism of processes and structures, which implies a continuous adaption to changing conditions. So with increasing complexity and dynamics efficient logistics networks, enterprises are doubtless of those which are able to adapt quickly and proactively to changes. These requirements are not met by current simple process-oriented concepts and systems. This launches the new concept of task-oriented logistics (Klingebiel 2009).

From the former view point of simple process orientation logistics, planning and control of material flows is defined in a result-oriented way. Processes carry out activities in defined frequencies or initiated by defined events, by a defined person or resource in charge, applying defined methods and structures. So a process possesses by definition a limited degree of freedom. It is necessary to change the process itself to adapt to changing environmental requirement.

In contrast to process oriented concepts, task oriented process concepts comprise degrees of freedom, which may be applied in terms of adaptivity: a logistics task is correlated with alternative activities which may access alternative resources within alternative structures to fulfil the task's target in different settings, i.e. system loads and events. Thus a process becomes not more than the realization of defined task under given conditions.

In the course of shortened order-to-delivery lead times, processes need to be accelerated, adapted and arranged flexibly and freely according to the needs. Especially the increasing dynamism and complexity forces producing enterprises to develop and establish efficient control mechanisms (Beckmann 1996). Basing on transparent, high-quality information these mechanisms shall secure flexibility and adaptivity of accelerated processes in order to react quickly and proactively to new environmental conditions.

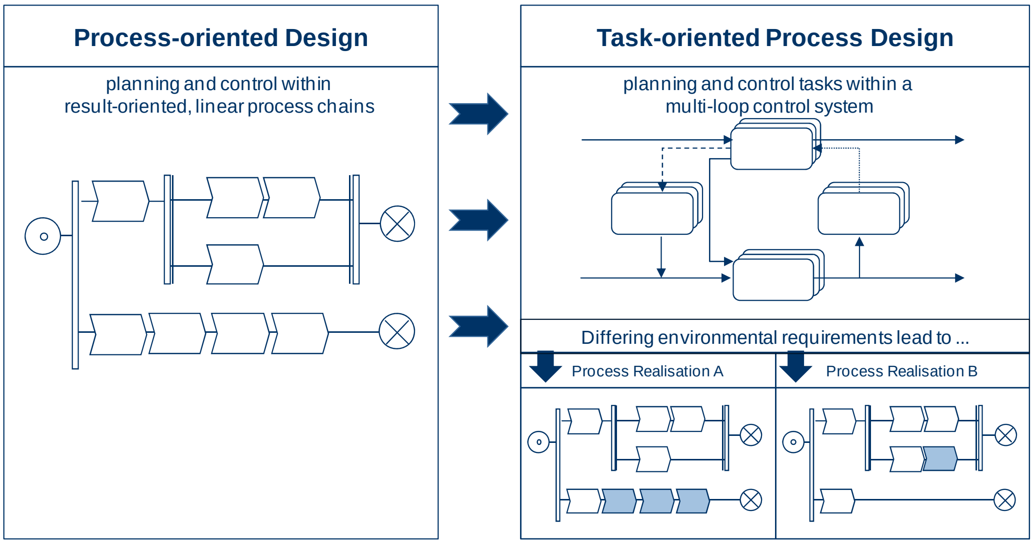

Figure 1: Task-Oriented Process Design

So as to approach customer-oriented adaptivity logistics planning and control need to be regarded as fulfilment of logistics tasks, which react continuously on feedback from other fulfilled tasks. This strives beyond today's result-oriented process: The prominent, simple flexibility exceeding adaptivity of logistics systems postulates to establish planning and control tasks as a multi-loop control system, thus emphasizing the non-linear dynamics. Positively used and controlled feedback causes a continuous adaptation, development and learning in the course of rapidly changing environmental requirements. Thus leading to the self adapting organization. Yet control loops of logistics tasks are not only essential within one organization but especially between autonomous organizations within a supply network.

To design a logistics system by task-oriented principle means to characterize tasks not processes, and establish efficient multi-loop control systems instead of result-oriented, linear process chains (see Figure 1). Then processes and process chain realize themselves optimally in dependence of environmental requirements. Nevertheless, as degrees of freedom exist not only concerning the activity itself but also for example concerning the executing instances, the executor as well as the precise activity needs to be decided or negotiated, sometimes even in short-term notice. Indispensable in this context are IT systems which offer the necessary communication and information technologies and may be adapted quickly according to the realizing processes.

Logistic Assistance Systems (LAS) can provide those features. They are designed as lean software systems and focus on specific logistics tasks and integrate selected methods for data management, information processing and supply chain planning. How these LAS can be used and designed in practice and which requirements they have to meet will be shown in the following chapters.

Logistic Assistant Systems (LAS)

Logistic Assistance Systems (LAS) are designed to assist logistics experts in planning by offering transparency about all relevant supply chain information and integrating specific decision support systems and planning approaches into one combined planning approach. Besides that, the idea of LAS is to provide a simple planning and software system, which can be adapted to new supply chains or planning situations with low effort. It can be easily integrated into a company's organization.

Therefore LAS integrate existing supply chain software concepts like Supply Chain Monitoring (SCMo) and Supply Chain Event Management (SCEM) to consolidate all relevant information along the supply chain. Further-more, LAS comprise additional APS functionality to allow for effective supply chain planning and execution applying current and high quality data. Thus, the LAS concept rests upon extended collaboration, consistent supply chain information, process transparency and planning functionality.

Consequently we divide this LAS concept into three blocks: Data acquisition and transparency, Decision support and Collaborative planning. These blocks allow dynamic and collaborative supply chain planning and will be introduced in the following sections.

Data Acquisition and Transparency

LAS need to consolidate all relevant information for a specified planning task. To achieve data acquisition and data transparency, LAS integrates functionalities of SCM concepts like SCMo and SCEM.

SCMo is a collaborative multi-level SCM concept that founds on software support for processing information between network partners (Odette 2003). The basic functionality is the exchange of production demands and inventory levels among business partners in a supply network to gain extended transparency and avoid time lags in information flow. Recent developments in SCMo applications integrate Supply Chain KPI Frameworks (Key Performance Indicators) and the assortment of graphical tools (e. g. predefined charts, cockpits or dashboards) for information presentation (Bäck and Gössler 2006). Exemplary KPIs that are applied in SCMo applications are forecasting accuracy and days of inventory (Hellingrath et al. 2008). Consequently, SCMo systems provide functionalities for monitoring the current status of a supply chain. Nevertheless, they lack methods for forecasting and planning, i.e. optimization and simulation.

On the operational level the concept of Supply Chain Event Management (SCEM) aims to support the execution of agreed plans by automatic identification of unacceptable deviations and suggestion of alternative solutions. Therefore, a SCEM system supports online data acquisition via tracking and tracing. It raises alerts if there are significant deviations between plan and current data.

LAS need to combine functionalities of both SCM concepts but stick to a simple approach: This system concept focuses on information transparency for decision makers without implementing a complex system requiring organizational changes. Therefore LAS provide standardized interfaces to different operational systems as well as tracking and tracing devices (e.g. XML specifications). This functionality is connected with existing data warehouses and business intelligence platforms. The key factor here is that all relevant task oriented information is collected and presented to the decision maker. The user interface is designed to be clear and simple; and the technological background of this functionality is designed to be flexible in order to be prepared for dynamically changing environments and supply chain structures. Figure 2 shows typical data sources, which are relevant to enable sufficient information transparency in global supply networks.

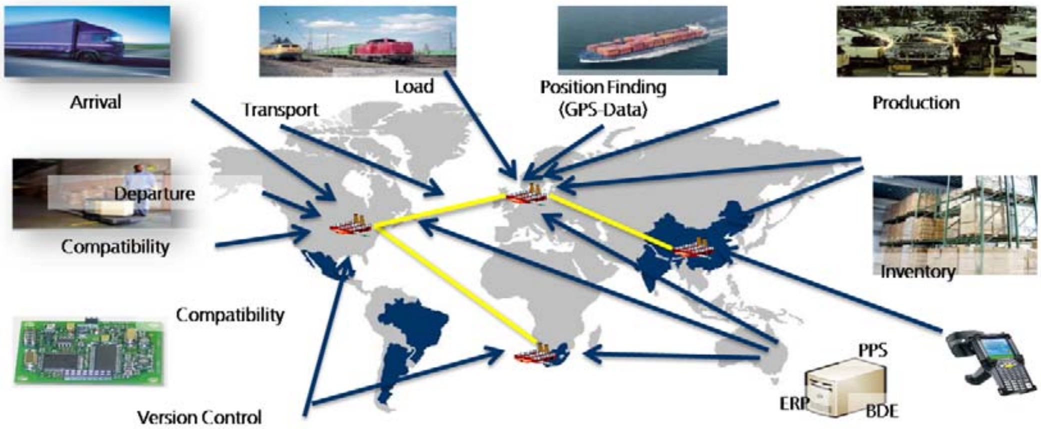

Figure 2: Forms of Data Acquisition and Consolidation

Decision Support

Decision Support (DSP) for LAS means that depending on the given logistics task the software system supports the human decision process in all its steps: decision preparation, option selection, decision execution and control. Depending on the focused planning task itself, LAS integrates different types of decision support concepts and systems:

LAS realizations typically integrate a simulation based concept to enable available-to-promise (ATP) and capable-to-promise (CTP) planning in complex supply networks. Therefore, the DSP module comprises a simulation component, which allows scenario based analysis of different demand, inventory and capacity situations within the supply network. Based on the current inventory situation (warehouse and transport stock) and a precise model of the supply network, LAS allow the simulation of future system's behaviour. Thus the feasibility of a change of plan (demand change or later estimated time of arrival of a ship) can be checked against reliably and thus be optimized ("what-if-analysis"). This so-called dynamic ATP allows for exact calculation if future demand could be fulfilled by then available inventory (see figure 3). This supports the user to control the chosen decision execution and its impact on the subsequent process (Toth and Wagenitz 2009).

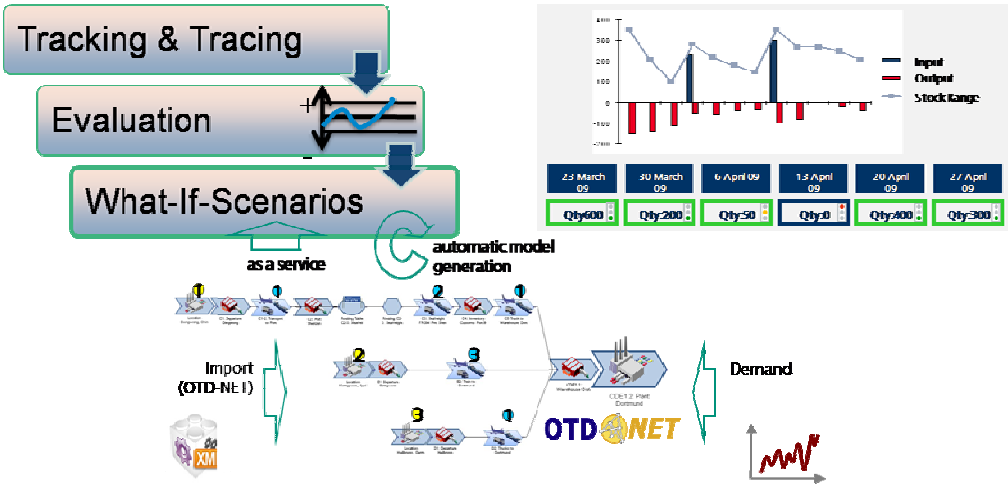

Figure 3: Simulation based ATP functionality and stock range calculation

The general idea of the DSP module is to offer flexible planning support by integrating different functionalities, i.e. simulation or optimization, as services into the architecture. In particular, service oriented architecture and easy configuration of LAS is a current research topic in this context.

Collaborative planning

For collaborative planning LAS combine data from all relevant network partners. Thus, information from all supply chain tiers may be used for information processing and decision support. Supporting the planning process, manual changes in data need to be tracked and documented by users. In addition to that it is necessary to integrate individual views by a dedicated role-based user management. This way proprietary information can be revealed to selected user groups, network partners or organizational departments. To support an enhanced communication process for collaborative planning, workflows and message systems must be applied (Bockholt et al. 2009).

To sum up, by providing decision support and collaborative planning, profound decisions can be made. But only if relevant and current supply chain information is given. With RFID-based LAS an early identification of possible bottleneck situations, supply shortages or surplus stocks is possible which yields cost and service benefits. Decision makers may intervene in an early stage to ward off cost-intensive additional processes. Especially for global order management, LAS provide company spanning and consequently holistic collaboration to stay competitive within rapid changing markets, as the following case illustrates.

Example from the Industry

Automotive original equipment manufacturers (OEM) produce in worldwide locations to enter emerging markets and to benefit from lower production costs. Also for cost reasons, parts, components, modules and systems are built into various models. For these reasons it is often not possible to bring all suppliers in the surroundings of an international plant. Especially suppliers of critical and high technologic parts are often located close to established OEM sites. Consequently due to a lack of local suppliers OEM production sites in emerging markets are often supplied over long distances. Here we notice multimodal transports with container vessels for main carriage.

Thus, since 2006 Volkswagen Groups' corporate IT department, Volkswagen Commercial Vehicles and Fraunhofer-Institute for Material Flow and Logistics (IML) have been developing and prototyping LAS in the field of global order management. One of these applications focuses on the power train supply chain for the VWN Crafter production in Hannover, Germany. These aggregates are produced in South Africa and delivered to Germany. Critical parts, which cannot be sourced locally, are delivered via CKD[1] from Europe to South Africa. The benefits of this CKD supply are seen in reduction of customs costs and the not necessary production infrastructure, especially in challenging, developing markets.

In opposition, shipping of parts to South Africa and final products, i.e. power trains, back to Germany takes several weeks (see figure 4). Since the safety stock in all supply chain levels has to be kept low it may not cover the entire time span from call-off to delivery. So production orders are released late in the process, call-offs are based on forecasted quantities (Bockholt et al. 2009). Consequently, volatile customer demand can only be met as long as there is enough stock in the pipeline, i.e. safety stock and additional inventories, which result from batch sizes or unexpected decrease of demand.

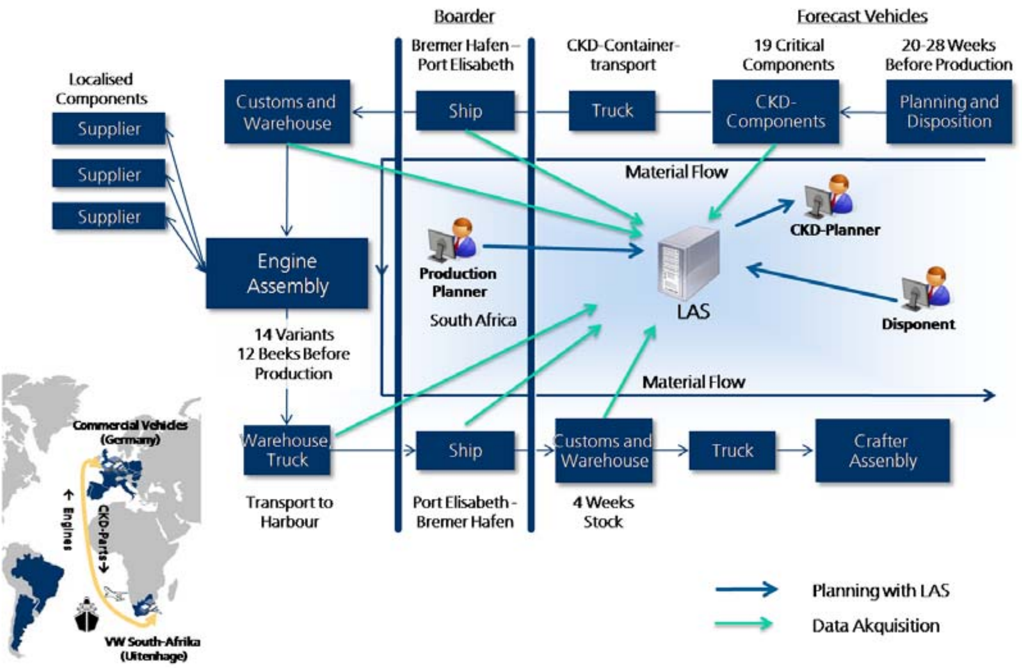

Figure 4: Example VWN Crafter Supply Chain

Thus, before the deployment of LAS order management experts from South Africa and Germany applied spread-sheet analysis to calculate availabilities of parts. They exchanged this information per email and adapted their planning accordingly (demand, capacity, and production program);

1 Completely Knocked Down (CKD): Pre-composed assembly kits are delivered as a whole to the assembly facility and assembled to a finale product.

resulting in much communication, non-reliable data and an accumulation of expensive airfreight processes. It has been quite transparent that in order to optimally mobilize this inventory, transparency of total demand, lead times and inventory is necessary.

As a result the LAS prototype, which counteracts these challenges for the engine CKD chain, has been developed to monitor the current state of this global power train supply chain, to forecast the behaviour of the supply chain and thus to give more flexibility to planning and sales departments.

The LAS prototype is based on a client-server architecture, providing access to all relevant information on inventory and demand, which are extracted from different data sources, i.e. RFID gates, and imported to a central supply chain database. This data also includes information about shipped parts and aggregates with their estimated time of arrival. Providing this availability of this data was seen as the basic precondition for answering capable-to-promise requests.

To realize this CTP-functionality an OTD-NET simulation (Wagenitz 2007) has been integrated into the LAS. OTD-NET has been developed as a platform for task-oriented network-analysis, in particular the analysis of order management processes in supply networks. Today OTD-NET synthesizes a wide range of broadened multidisciplinary concepts. These concepts are taken from business process simulation, supply chain management (SCM) and material flow simulation.

By application of OTD-NET future inventory levels can be forecasted for every item. The results are processed into customized views; for example a potential “running out of stock” situation is indicated using traffic light.

The Crafter LAS has been launched in August 2007. By deployment of the LAS approach, it was possible to provide integrated data and planning views for all partners. The integrated simulation component offered ATP and CTP functionalities to avoid shortage or overcapacity situations. The resulting quality of planning and forecasting allowed for new inventory strategies with lower stock levels. This was resulting in a decrease in airfreight by 95% and significant cost savings (Deiseroth et al. 2008).

Recent projects have extended this approach: In the automotive industry internal logistics service providers supply various production sites in emerging markets.

Serving several customers, these divisions have to avoid shortage situations while demand is varying and delivery time is long. Thus the complexity of the supply chain is increasing with each stakeholder and each part. The LAS approach was confronted with new requirements.

The logical step here is to replace the software client architecture by a new web based application as this architecture provides the functionalities for significantly higher data volume. An integrated user management regulates the access to information and provides data security. Input data is extracted from different data warehouses, operative systems and RFID-tracked information. Creating visibility over all integrated supply chains and simulating future scenarios now allows a stabilised planning and reduction of costs to a wide extent. A prototype is currently being deployed by Fraunhofer IML and Volkswagen.

Another project extends our approach to consider production capacities from suppliers as further input data. In future customer orders, resulting demand requirements, inventory levels and supplier capacities will be consolidated within the supply chain model. In addition, energy efficiency analysis, e.g. CO_2 emissions of transports, will be integrated. This LAS system will be released in the second quarter of 2010.

All projects described above have proven the applicability of the LAS approach. But all these projects also made clear that data quality is the major problem. For example ETA information (Estimated Time of Arrival) is typically calculated with the departure of a transport and never updated. After arriving at the destination, containers often are physically available at customer sites, but not registered so that the information is not available in the operational systems. That implies information inconsistencies and data inaccuracy of several working days. Applying RFID technology is one of the most promising approaches to overcome these problems. The current state of a supply chain is registered constantly and LAS can make use of this information to offer a new dimension of data and planning quality. Actual research projects are showing outstanding prospects for this application of LAS with RFID technology. This approach finally closes the gap between simple traceability to effective global order management, thus tapping the potential of RFID implementations.

Conclusion and Prospects

Today's supply chains may be recognized as highly dynamic systems which require flexible planning and execution processes. Furthermore new technologies like RFID and CEP offer a new level of transparency and planning quality. Yet, to allow for dynamic task-oriented planning while handling the flood of supply chain data generated by RFID technology, a new type of supply chain planning and control software is required.

This paper introduced RFID-based Logistic Assistance Systems as a new software paradigm. We could show that LAS combine a holistic approach, which faces all challenges of collecting, evaluating, forecasting and presenting information for effective global order management with a lean and easy to launch architecture. LAS combine existing supply chain software concepts like Supply Chain Monitoring (SCMo) and Supply Chain Event Management (SCEM) to consolidate all relevant information along the supply chain and integrate specific decision support systems and planning approaches (like ATP or CTP) into one combined planning approach.

By integration of CEP concepts it is possible to control time critical processes continuously and in real-time. Thus providing analysis and interpretation of RFID-based supply chain events within their chronology. A new quality of planning is accomplished.

The described case could prove the applicability of this new approach. For the VWN Crafter LAS have provided an integrated approach for collaborative planning and scheduling of supply networks for medium-term and operational planning horizons. The Crafter LAS system was awarded with the elog@istics award of the German AKJ automotive group, underlining the outstanding results.

Nevertheless we expect still more potential. It is mandatory for the success of RFID-technology to identify further cost reducing and performance relevant functionalities which legitimate the high investments for new hardware and process concepts. Consequently one of our next steps is the realization of additional services beyond pure traceability, event management, ATP and CTP. This includes cost benefit sharing, intelligent RFID-based order processing and automatic control. Furthermore we work on data as well as process standards for the application of RFID-based systems for global order management. We are positive that thereby easy data exchange and closed control loops for cross-company supply chains will be realizable. Furthermore the integration of small and medium enterprises will be easy to handle.

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Strategic Positioning of Tsunami Detection Buoys in the Caribbean Sea

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Abstract

The December 2004 Indian Ocean tsunami increased global awareness to the destructive nature of tsunamis. International effort in constructing a tsunami warning system (TWS) in the Indian Ocean followed. The issue of constructing a cost- and performance-effective TWS is still on the agenda in a number of areas world-wide. This includes the countries bordering the Caribbean Sea. The purpose of this paper is to examine the effectiveness of the current Caribbean tsunami warning system and, where required, to suggest how its performance can be improved. It is found that relatively few additional detectors are required to improve performance.

Keywords*:* Tsunami warning system, maximal covering location problem

Introduction

On 26 December 2004 a 9.3 magnitude earthquake occurred on the sea floor near the province of Aceh, in northern Sumatra, Indonesia. It generated a tsunami that resulted in the deaths of more than 240,000 people across 11 nations. This disaster motivated a number of national and international initiatives aimed at establishing reliable and robust tsunami warning systems (TWS). It was proposed that these systems utilise the existing global network of seismic monitors and be linked with sea-level monitoring stations, deep-ocean tsunami monitoring buoys and local and national warning and disaster management centres. With the global seismic network well–established and fully operational, this study will focus on the remaining detection component of a TWS, the sea-level monitors and deep-sea pressure sensors attached to deep ocean buoys. We will focus our study on one geographical area of the global detection network, the Caribbean Sea. Specifically then, this study will examine the effectiveness of the current configuration of sea-level stations and tsunami detection buoys as measured by the receipt of timely warning to the greatest population of the villages, towns and cities surrounding the Caribbean Sea. We will also examine the potential performance of the planned changes to the existing system using the same performance measure. Based on the results of these examinations, we will suggest ways in which the effectiveness of the current configuration can be improved.

In the sections that follow, an approach to measuring the effectiveness of the current configuration is suggested and outlined, the data and solution approach described, and the analysis of the current configuration presented and discussed. The paper then goes on to examine how the current configuration could be improved with suggestions for future research following.

The Problem

Given the extent and likely performance of the current configuration of sea-level stations in the Caribbean, we will seek to determine the optimal locations of tsunami warning buoys in order to provide the largest time available for warning populations of the approach of a tsunami. This is applied to the coastal regions bordering the Caribbean Sea. This is an optimal location problem and is most closely related to the maximal coverage location problem (MCLP). According to Berman and Krass (2002), the objective of a MLCP is to establish a framework of facilities in order to maximize the total weight of covered customers, where a customer is considered covered if they are located at most a specified distance away from the closest facility. Here, *covered* may be described in terms of the timeliness of a warning being received by a population centre, which is directly related to the distance from a detection site. The parallel to the weights in the objective are then the populations of the centres in the region.

Literature

Braddock and Carmody (2001) provide the first investigation of the problem of optimally locating tsunami detection sites. They applied their model to an investigation of performance of a limited number of proposed tsunami detection buoys in the Pacific Ocean. They developed a 0-1 integer program where the objective was to provide the maximum warning to population centres as measured by the numbers of lives that could be saved (the warning potential). The decisions were simply whether a buoy was sited at a particular location or not, and the constraint was the number of buoys available for allocation. Their model was solved using enumeration. Their study revealed that the warning potential could be improved by the addition of a subset of buoys, specifically through the deployment of two or three detection buoys. Further, their warning potential did not improve beyond the addition of four or more detectors.

Groen et al (2010) extended the application of the Braddock and Carmody model to evaluate the proposed tsunami warning system in the Indian Ocean Region. Given that the tsunami warning system for the Indian Ocean was poorly developed at the time of their study, they included sea-level stations as well as warning buoys in their study. They concluded that only 10 of the 40 initially proposed sea-level monitors and buoy sites were required to provide the maximum warning potential for the region.

A Model for Maximising the Effectiveness of a Tsunami Warning System

The model selected for use in this study is based on that of Braddock and Carmody (2001). The objective of the model is to maximize the warning potential, a proportionate measure of the total population that will receive a timely warning to evacuate. The warning potential is a function of the deployment vector, the set of locations of buoys and monitors. As the region of the Caribbean Sea has a comprehensive system of sea-level stations involved in tsunami detection, it is only necessary to determine whether the current number and location of DART buoys optimises the warning potential. Mathematically, this may be expressed as:

Maximise $E(y)$
subject to

$$\sum_{w=1}^{W} y_w \leq X, \qquad y_w = \begin{cases} 0 \text{ if site } w \text{ is not occupied by a buoy} \\ 1 \text{ if site } w \text{ is occupied by a buoy.} \end{cases}.$$

Here, the expected total warning potential is $E(y)$. It is a function of the deployment variables, y_w, with $y = (y_1, y_2, \dots, y_w)$. The complexity of the model lies in the detail of how the warning potential is calculated. How this calculation is undertaken is outlined in the following paragraphs.

In order to determine whether the population centres of the region receive a timely warning three times must be calculated: the time taken by the tsunami to travel from the generation point to the population centre, the time taken by the tsunami to travel from the generation point to the detection site, and the time taken for the detection site to communicate with the warning centre and thence the population centre. One time is specified. This time is set by the management of the TWS. It is the minimum time required in order to evacuate those persons likely to be affected by the tsunami. In this study a number of different values for this time are considered. The sum of the last three times must then be less than the first for a timely warning to be received.

Computation of the two groups of tsunami travel times requires the formation of two matrices specifying the distances between the generation points and detector sites, and the generation points and population centres. The tsunami travel times are then computed assuming an average wave speed. All distances used in the time calculations are based on the Method of Great Circles. (A brief description of this method can be found in the Appendix.) Calculating the travel time of the tsunami to the population centre is straightforward. Calculating the time taken for a warning to reach the population centres is only slightly less so.

Let the sites of the candidate tsunami detection buoys and existing sea-level stations be denoted by B_w = (latitude, longitude)$_w$, for $w = 1, \dots, W$, where W describes the total number of available detection sites. Sample points from the common tsunamigenic regions in the Caribbean Sea are denoted by G_u = (latitude, longitude)$_u$, for $u = 1, \dots, U$, where U represents the total number of sample points chosen. Population centres are described by P_v = (latitude, longitude, population)$_v$, for $v = 1, \dots, V$ and p_v = population size in P_v, where V denotes the total number of population centres included. The population size at the centre is used as a proxy for the number of people that may be affected by a tsunami, as the actual population at risk depends on the size of the tsunami and the geography of the population centre. The time taken for the tsunami to travel to each population centre will be represented by $t_{u,v}$, the tsunami travel time from G_u to P_v.

The first component in determining the time taken for a warning to reach a population centre is the time taken by the tsunami generated at G_u to reach a detection site B_w. The time t_d is the processing and transmission time to confirm the detection of a tsunami by the detection point B_w. (B_w may represent a sea-level station or a DART buoy yielding different t_d values.)

Then define $t_w = t_{u,w} + t_d$ as the total time taken to issue a warning from detection point B_w for a tsunami generation point G_u. The minimum value of t_w across all detection points would be the time taken to issue a tsunami warning for tsunami generation point G_u. This minimum time is denoted by t_w*.

$$t_w^* = \operatorname*{Min}_{w} \text{(time taken to issue a tsunami warning for } G_u\text{, with } y_w = 1\text{)}$$

The population P_v can be provided with a timely warning as long as $t_w^* + r_v < t_{u,v}$ where r_v is taken to be the public warning time.

The warning potential for a given population centre P_v, for a tsunami generated at G_u, and for a deployment of detectors, y, is given by $e_{u,v}(y)$ where:

$$e_{u,v}(y) = \begin{cases} 0, & t_w^* + r_v - t_{u,v} \geq 0 \\ p_v, & t_w^* + r_v - t_{u,v} < 0 \end{cases}.$$

That is, if timely warning is not received, $e_{u,v}(y)$ takes the value of 0, while if a population can receive a timely warning, the size of the population is taken. The total warning potential is then calculated by summing all warning potentials, standardising over the total population of all centres (so that the quantity in the square brackets is the proportion of the total population warned for a given tsunami generation point), then summing over all generation points and standardizing by the total number of generation points:

$$E(y) = \frac{1}{U}\sum_{u=1}^{U}\left[\frac{\sum_{v=1}^{V} e_{u,v}(y)}{\sum_{v=1}^{V} p_v}\right]$$

The total warning potential is thus a dimensionless number between 0 (least preferable) and 1 (most preferable), and provides a measure of the effectiveness of the detection system.

Data for model

Response times

When changes in sea pressure each the Bottom Pressure Recorder (BPR) of a DART buoy, the buoy can communicate data to tsunami warning centres in less than 3 minutes (Meinig et al, 2005). On the other hand, sea-level monitoring stations in the Caribbean are currently expected to transmit data within 6 minutes. As a consequence, the detection times used in the model were based on whether the site was a sea-level station or a DART buoy.

In order to estimate the response times of a population to a tsunami warning, a minimum time of 30 minutes was used. This was based on information obtained in the Implementation Plan for the Caribbean region (Intergovernmental Oceanographic Commission of UNESCO, 2008) where tsunami warnings are sent out immediately to population centres if the tsunami wave travel time to the population centre is less than 40 minutes. Further checking is undertaken when the estimated arrival time of the tsunami exceeds 40 minutes. As a consequence, we also examined population response times greater than this, specifically, population response times of 1hr, 2 hrs and 3hrs.

Tsunami wave speed and height

In the deep ocean, tsunami waves are inconspicuous, even though they travel at speeds between 500 to 1000 km/hr. It is only when they approach the shore that they become catastrophic, reaching heights of 10 metres or more. Unlike waves generated by wind which have a period of seconds, tsunami waves in the deep ocean have a period in the order of hours. The distance between tsunami wave crests can be as much as 650 kilometres with a height of only 3 centimetres, with the waves oscillating from the sea floor to the surface. A tsunami is comprised of a set of such waves, the duration of which may range from several minutes to hours or even days. In this study an average wave speed of 600km/hr was used.

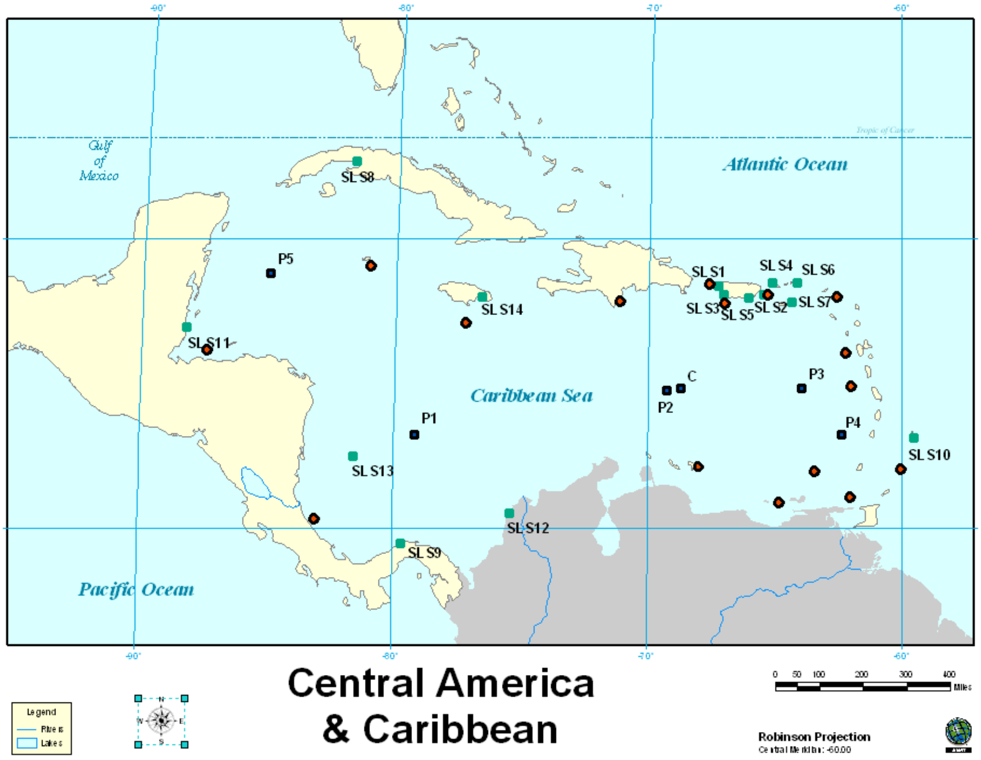

Figure 1. DART buoy and sea-level station locations and tsunami generation points. (ArcGIS 2010)

<u>Population centres</u>

Forty-eight population centres have been selected as being potentially affected by tsunami inundation. The data required to implement the model for the Caribbean Sea includes the location, size and height above sea-level of the population centres bordering the sea. Representative population centres in the tsunami risk zones were selected after studying and analyzing the coastal region surrounding the Caribbean Sea. The location, size and height above sea-level of the population centres are listed in Table A1 of the Appendix.

<u>Locations of sea-level stations and DART buoys</u>

The location of sea-level stations and DART buoys for the existing TWS can be found in Global Sea-Level Observing System (2009) and NOAA National Data Buoy Center (2009) and in Figure 1. The current full configuration of the TWS includes 1 DART buoy and 9 sea-level stations. The planned full configuration includes an additional 5 sea-level stations (Intergovernmental Oceanographic Commission of UNESCO, 2008).

Candidate locations for buoy deployment in the Caribbean Sea were determined by examining the historical record of tsunami generation sites and earthquakes for the region - sufficient distance between the location of the geological triggers of tsunamis from DART buoys is required so as not to confuse the Bottom Pressure Recorder (BPR) of the detection buoy, with seismic surface waves (Rayleigh waves). At the same time, there is a trade-off with minimising the distance to triggers to allow for earliest possible detection. In addition, the sites where DART buoys were required to satisfy the following criteria (found in Spillane et al, 2008) - sea depth between 1500 and 6000 metres, relatively uniform sea depth, no rugged sea-floor terrain. Data for the DART buoys sites and the current and planned locations of sea-level stations are listed in Tables A2.1 and A2.2 of the Appendix.

Potential tsunamigenic event locations

Evaluation and selection of tsunami generation points in the Caribbean region is based on magnitude and frequency of earthquakes, subduction zones/ fault lines and volcanic activity. While earthquakes are difficult to predict, their location can be estimated by examining historical earthquakes and through the location of subduction zones (Pellerin, 2005). The location of the generation points used is given in Table A3 of the Appendix and illustrated in Figure 1.

Data preprocessing

The required Great Circle distances between locations were calculated using online tools available from APSalin (2009).

Solution approach

As the number of tsunamigenic sites is relatively small, examining the performance of the current TWS by using enumeration is not onerous. The most significant contributor to the computational effort in examining the performance of the current configuration of the TWS is the number of population centres included. Solving by enumeration also has the advantage that it is possible to not only determine best performance of the current and proposed systems of sea-level stations and DART buoys that contribute to this performance, but also to determine alternative configurations yielding comparable
performance. Worst case performance, where some gauges or DART buoys are not operational, can also be examined using enumeration.

Results

The current configurations of sea-level stations and DART buoys

The current tsunami warning system in the Caribbean Sea consists of a single DART buoy (42407) and 9 sea-level stations listed in the Appendix (Tables A2.1 and A2.2). Intergovernmental Oceanographic Commission of UNESCO (2008) identifies 5 more sea-level stations that have been planned for the region. There are a further 11 ocean buoys in the region of the Caribbean under study that monitor sea-level. However, these buoys play no role in the regional TWS.

Table 1 lists the results of tsunami warning potential for current and planned configurations as outlined in the Implementation Plan (IOC 2008). Clearly, increasing the warning time reduces the warning potential, with a smaller proportion of the regional population receiving a timely warning. It is also obvious that increasing the number of detectors increases the warning potential. The results comparison of the current configuration (DART buoy plus all currently active real-time reporting stations) against the planned configuration indicates an improvement of approximately 35% in performance of warning potential for a 60 minute warning to the population centres. A smaller improvement, approximately 10%, is associated with a warning time of 30 minutes.

Improving performance of the TWS for the Caribbean

It was hypothesized that increasing the number of DART buoys in the Caribbean Sea and/or locating them at strategic positions could improve the performance of the TWS as measured by the warning potential. Tsunami warning potentials were calculated by using enumeration and considering different buoy combinations to supplement the currently planned sea-level station configuration.

For a warning time of 30 minutes, the current buoy (C) is included in all combinations of stations and buoys. Further, the largest warning potential is achieved for a minimum of 4 buoys, though the increase in warning potential from 2 buoys is only slight.

Table 1. Current and Planned Tsunami Warning Potential

	Tsunami Warning Potential		
	Warning time = 30 min	**Warning time = 60 min**	**Warning time = 120 min**
Current DART Buoy only	0.5025	0.2718	0.0706
Current Sea-Level Stations only	0.6895	0.4605	0.1338
Current Full Configuration	0.7774	0.4689	0.1349
Planned Sea-Level Stations only	0.7672	0.6273	0.2348
Planned Full Configuration	0.8550	0.6338	0.2359

Current Full Configuration = DART Buoy 42407 & 9 Real-time Sea-Level Stations

Planned Full Configuration = DART Buoy 42407 & 14 Real-time Sea-Level Stations

Table 2. Maximum Warning Potentials for buoy combinations

	Maximum Tsunami Warning Potential					
	Warning Time = 30 min		**Warning Time = 60 min**		**Warning Time = 120 min**	
Single Buoy	C	0.8550	P4	0.6731	P4	0.2774
2 Buoy combinations	C+P4	0.8654	P3+P4	0.6899	P4+P5	0.2787
3 Buoy combinations	C+P4+P5	0.8667	P3+P4+P5	0.6920	C+P4+P5	0.2798
4 Buoy combinations	C+P3+P4+P5	0.8670	C+P3+P4+P5	0.6983	C +P4+P5+, P1, P2 or P3	0.2798
5 Buoy combinations	C+P3+P4+P5+, P1 or P2	0.8670	C+P3+P4+P5+, P1 or P2	0.6983	C+ P4+P5+, any 2 of P1, P2 or P3	0.2798
6 Buoy Combination	All	0.8670	All	0.6983	All	0.2798

However, when the warning time is increased to 60 minutes, the current buoy does not appear in the optimal configuration until 4 buoys are included in the proposed TWS. In fact, the inclusion of the current buoy in the 4 buoy combination is only a marginal improvement in relation to including proposed sites 1 (P1) or 2 (P2). The proposed sites 3, 4 and 5, appear to be of influence in determining the maximum warning potential for a warning time of 60 minutes.

When the warning time is raised to 120 minutes, the current buoy (C) again failed to appear in the optimal configuration for single and 2 buoy combinations. The proposed sites 4 (P4) and 5 (P5) appear to have a greater impact on the warning potential than the current buoy, in this warning time zone. However, the 3 buoy combination comprising of P4, P5 and the current buoy yields the maximum warning potential for a warning time of 120 minutes, with a marginal rise over the 2 buoy result.

Our evaluation further revealed that if a warning time of 180 minutes was expected in the Caribbean Sea region, then only 7- 8% of the target population could be provided timely warning. Neither the increase in the number of buoys deployed nor changes to the buoy combinations could provide any meaningful gain to the warning potential, when the warning time was taken as 180 minutes. This result, and those for a 120 minute warning time, highlights the need for a speedy response to warnings issued. A quick response by populations is more likely to be obtained through education and familiarization which is a role for local and regional warning centres.

As has been seen in the study by Braddock and Carmody (2001) and Groen *et al* (2010), the warning potential ceases to increase for an increasing number of buoys. In this case, there is no increase in warning potential past four buoys. This suggests that no more than three additional buoys are required in the Caribbean in order to ensure the maximum warning potential is reached.

Conclusion

In this study, possible improvements in the current and planned tsunami early warning systems for the region surrounding the Caribbean Sea were examined. This examination was based on the calculation of total warning potential for 48 coastal population centres assuming 16 equally likely tsunami generation points. The results of the study show that an improvement in the impact of the Caribbean TWS can be achieved by the addition of a small number of DART buoys. This improvement is of the order of 50% over the current configuration of DART buoy and sea-level stations, and approximately 10% over the planned configuration for a warning time of 60 minutes. No more than three such buoys are required to achieve this goal. A 9% increase in warning potential can be achieved with the addition of only one further buoy and the relocation of the existing buoy.

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Appendix

<u>Distance calculation</u>

The calculation of the following distances is based on the method of Great Circles. It is used to find the distances between Tsunami Generation Points and detection sites, and the Tsunami Generation Points and Population Centres. The method of Great Circles calculates spherical distances from pairs of latitude and longitude values using the shortest path between two points on a sphere, a segment of a great circle. A great circle is a circle defined by the intersection of the surface of the Earth and any plane that passes through the centre of the Earth. Thus between any two points on the Earth which are not directly opposite each other, there is a unique great circle. The two points separate the great circle into two arcs. The length of the shorter arc is the great-circle distance between the points.

The great circle (geodesic) distance between two points, P_1 and P_2, located at latitude x_1 and longitude x_2 of (x_{11}, x_{21}) and (x_{12}, x_{22}) on a sphere of radius a is
$d = a \cos^{-1} \cos x_{11} \cos x_{12} \cos (x_{21} - x_{22}) + \sin x_{11} \sin x_{12}$

This formula assumes that the Earth is spherical with a fixed radius of a. When the flattening of the Earth is taken into by approximating the shape of the earth to a spheroid or ellipsoid, the radius will be a function of latitude. The Great Circle Distances in this study was calculated using the reference earth ellipsoid model, World Geodetic System 1984 (WGS 84).

When the region between a tsunami generation point and a population centre/ detector includes a land mass, the tsunami wave may not reach the potential destination. In such circumstances, a travel time many orders of magnitude higher than that based on the Great Circle distance is used.

Input data

Table A1 – Population Centres

Country	Centre ID	Population Centre	Latitude (N)	Longitude (W)	Population (x1000)
Anguilla	1	Anguilla	18.4	63.18	14.4
Antigua and Barbuda	2	St. John's, Antigua	17.081	61.857	46.0
	3	Codrington, Barbuda	17.633	61.833	1.4
Aruba	4	Aruba	12.52	70.02	103.0
Barbados	5	Bridgetown	13.095	59.618	99.0
Belize	6	Belize city	17.483	88.183	71.0
Bonaire	7	Bonaire	12.11	68.85	14.0
British Virgin Islands	8	Road Town, Tortola	18.433	64.617	9.5
Cayman Islands	9	George Town	19.303	81.386	22.0
Colombia	10	Cartagena	10.4	75.5	1,239.4
	11	Santa Marta-Riohacha	11.242	74.205	804.0
Costa Rica	12	Peurto Limon	9.983	83.033	108.8
Cuba	13	Manzanillo	20.340	77.109	130.7
Curaçao	14	Curaçao	12.183	69.000	173.0
Dominica	15	Roseau	15.301	61.388	14.8
Dominican Republic	16	Barahona	18.167	71.25	141.9
	17	La Romana	18.417	68.967	250.0
	18	Santa Domingo	18.5	69.983	2,253.4
Grenada	19	St George's-Gouyave	12.05	61.75	11.9
Guatemala	20	Livingston-Puerto Barrios	15.833	88.75	19.2
Guadeloupe	21	Basse-Terre	16.028	61.717	11.4
	22	Port Louis	16.417	61.517	5.5
	23	Pointe-a-Pitre	16.233	61.517	18.2
Haiti	24	Port-au-Prince	18.539	72.335	1,234.7
	25	Les Cayes	18.168	73.758	59.3
	26	Gonaïves	19.45	72.683	85.0
Honduras	27	La Ceiba-Puerto Cortez	15.783	87.45	77.3
Jamaica	28	Kingston	17.997	76.794	937.7
	29	Sananna-la-Mar	18.217	78.133	19.1
	30	Montego Bay	18.467	77.917	17.2
Nicaragua	31	Puerto Cabezas	14.033	83.383	33.6
Martinique	32	Fort-de-France	14.6	61.083	90.0
Mexico	33	Cancun	21.174	86.847	542.0
Panama	34	Colon	9.359	79.901	76.6
Puerto Rico	35	Guayama	17.984	66.114	28.6

Country	Centre ID	Population Centre	Latitude (N)	Longitude (W)	Population (x1000)
	36	Yabucoa	18.05	65.879	7.0
Saba	37	Saba	17.633	63.233	1.4
Saint Kitts and Nevis	38	Basseterre	17.3	62.717	12.9
Sint Eustatius	39	Sint Eustatius	7.5	62.967	2.5
St. Barts	40	St. Barts	17.9	62.833	8.4
St. Martin	41	St. Martin	18.067	63.05	72.8
Trinidad and Tobago	42	Port-of-Spain	10.65	61.517	49.6
Turks & Caicos Islands	43	Providenciales	21.783	72.283	30.5
US Virgin Islands	44	Charlotte Amalie, St Thomas,	18.365	64.924	19.0
	45	Cruz Bay, St John	18.333	64.733	2.7
	46	St. Croix	17.75	64.75	6.5
Venezuela	47	Barcelona-Cumana	10.133	64.717	424.7
	48	Puerto Cabello	10.529	68.083	174.0

Table A2.1 - Current and Candidate Locations for tsunami detection buoys

Buoy ID	Lat. (N)	Long. (W)	Comment	Buoy ID	Lat. (N)	Long. (W)	Comment
C	15.260	68.241	Current DART Buoy 42407	P3	15.000	64.000	Candidate
P1	13.000	79.000	Candidate	P4	13.000	62.000	Candidate
P2	15.000	69.000	Candidate	P5	19.000	85.000	Candidate

Table A2.2 – Current and Planned Sea-Level Stations

SLS ID	Latitude (N)	Longitude (W)	Location	Status
1	17.972	67.047	Magueyes Islands, Puerto Rico	Current
2	18.055	65.833	Yabucoa Harbor, Puerto Rico	Current
3	18.218	67.159	Mayaguez, Puerto Rico	Current
4	18.094	65.471	Vieques, Puerto Rico	Current
5	17.973	66.762	Penuelas, Puerto Rico	Current
6	18.335	64.920	Charlotte Amalie, Virgin Islands	Current
7	17.784	64.762	St. Croix, US Virgin Islands	Current
8	23.100	82.467	Siboney, Cuba	Current
9	9.367	79.883	Coco Solo, Panama	Current
10	13.095	59.618	Bridgetown, Barbados	Planned
11	17.483	88.183	Baize City, Baize	Planned
12	10.400	75.550	Cartagena, Colombia	Planned
13	12.500	81.800	Isala de San Andres, Colombia	Planned
14	17.997	76.794	Kingston, Jamaica	Planned

Table A3 – Tsunami Generation Points

TGP ID	Latitude (N)	Longitude (W)	Location
1	14.943	61.244	Martinique Region, Windward Islands
2	18.000	64.750	Anegada trough, East of Virgin islands
3	18.958	81.409	Cayman Islands, West of Jamaica
4	18.500	67.500	Mona Passage, Between Puerto Rico and Dominican Republic
5	17.750	67.000	Southern Pueto Rico
6	11.000	62.000	South Caribbean, Between Greneda and Venezuela
7	16.000	62.000	West of Gaudeloupe
8	12.000	68.000	South Caribbean, Lesser Antillers, close to Venezuela
9	18.000	62.000	Leeward Islands, North of Antigua
10	12.000	60.000	South East Caribbean
11	16.000	88.000	Close to Belize
12	10.000	64.100	Between Venezuela and Barbados
13	17.000	76.800	Close to Jamaica
14	18.000	70.700	Close to Hispaniola
15	10.000	82.900	Close to Costa Rica
16	12.000	63.600	Close to Cumana, Venezuela

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Component Commonality Strategies to Achieve Mass Customization: When a Strategy Becomes Better than the Others?

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Abstract

The strategy shifting from make-to-stock (MTS) to make-to-order (MTO) – in order to gain economies of scale and scope – in terms of product varieties, leads the trends in using product proliferation strategy. Component commonality is one of the most popular supply chain strategies to cope with challenges of product proliferation. Distinctive Parts (DP) and Pure Component Commonality (PCC) strategies in component commonality have been researched previously. These two strategies are not sufficient in a multiple layers product configuration because they do not reach optimal value of degree of commonality in minimizing total costs. Therefore, we introduce a new strategy called Mixed Component Commonality (MCC). The benefit of MCC can be found in a multiple layers product configuration, even under deterministic demand situation. In MCC strategy, common components are generally equipped with extended functions such as additional conjunction to attach two different end-products and have to meet the quality standard of the higher-level end-product. In this paper, we develops a mathematical model to determine the most optimal strategy in component commonality and to identify situation that a strategy of component commonality becomes better than the others. A nonlinear programming model for two-segmented-products, multiple layers, and multiple periods inventory model with deterministic demand scenarios is developed to minimize total costs (*i.e.* material unit cost, ordering cost and inventory holding cost). Sensitivity analysis shows trades-off of material cost, inventory holding cost, and ordering cost in chosing the best strategy. We find that the MCC strategy are beneficial to encounter PCC pitfalls in reducing inventory cost. In contrast, DP strategy is more preferable than PCC strategy in the condition when the price of second layer of common components is more expensive than the price of second layer of unique components of lower-level end-product. This is strongly related to our single-cycle time policy.

Key Words: Inventory theory and applications; deterministic demand; multi-layer product configuration; mixed component commonality.

Introduction

Rapid changes in technology and globalization are common trends in today's business environment. One of immediate responses to this new environment is increase of product proliferation (Lee, 1996). Product proliferation is a common challenge for companies providing customized products. To cope with this challenge, companies usually incorporate strategies such as component commonality, postponement, and/or delayed differentiation in their supply chain systems.

Component commonality is one of the most popular supply chain strategies to cope with challenges of product proliferation such as difficulties in estimating demand, controlling inventory, and providing high customer satisfaction level. Due to risk pooling, component commonality advocates the utilization of one or more common components to replace a number of distinctive parts in various products so that safety stock can be reduced. In addition to the component commonality strategy, various supply chain strategies have been explored to provide a wide range of product varieties in a cost efficient way (also referred to as mass customization). Many companies are shifting their supply chain strategies from make-to-stock (MTS) to make-to-order (MTO) to achieve mass customization. An MTO strategy comes at a price; however, customers must wait longer for their customized products. Incorporating delayed differentiation in an MTO environment might potentially reduce waiting time for customers, since the generic parts/components of the products can be made before the customer order is received. In brief, component commonality is important for a variety of product options being offered to customers with a relatively short delivery time, such as automobiles and personal computers.

Distinctive Parts (DP) and Pure Component Commonality (PCC) strategies in product proliferation have been researched previously for a single-layer product configuration. In DP strategy, common components in all layers will never be utilized. This strategy becomes beneficial when unique components utilization elicits the decrease of material cost. In PCC strategy, unique components in all layers will never be utilized. This strategy becomes beneficial to replace a number of distinctive parts in various products so that the safety stock can be reduced due to risk pooling.

Only DP and PCC are not sufficient when all supply chain members are engaged in multi-layer product configuration procurement, because these two strategies do not reach optimal value of degree of commonality in minimizing total costs. Therefore, we introduce a new strategy called Mixed Component Commonality (MCC). Significant benefit of MCC can be found in a multi-layer product configuration. In MCC strategy, the common components are generally equipped with an extended function such as additional conjunction to attach two different end-products, given that they have to meet the quality standard of the higher-level end-product. Merits of using MCC depends on the ordering cost and material cost. This strategy gives trading-off balance on the purpose of decreasing material cost and at the same time reducing risk pooling, but spending some ordering cost.

We realize that the assemble-to-order (ATO) system emerges in manufacturing environment where many finished products are assembled from a relatively small set of standard components and subassemblies. In this typical environment, components and subassemblies are acquired according to forecasts, while finished products are assembled only after actual customers' orders have been received. In other words, components and subassemblies are replenished in an MTS way, but finished products are assembled in an MTO manner. Example of ATO systems can be found in various industries producing customer goods such as automobiles and PC, where customers are offered a variety of product options with a relatively short delivery time. A hybrid planning approach of MCC is particularly advantageous for this situation because it allows two or more products using the same components in their assembly.

A real example of the MCC strategy in ATO system can be observed from the Personal Computer (PC) industry. Most of PC manufacturers utilize Pentium CPU (Central Processing Unit) in their high-end PCs and Celeron CPU (Central Processing Unit) in their low-end PCs. In general, there are three types of motherboard chip sets available, *i.e.* the chip set that supports only the Pentium CPU, the chip set that supports only the Celeron CPU, and the chip set that supports both CPUs. PC manufacturers often utilize combinations of these three types of chip sets in their PCs. Each type of motherboard chip itself will be supported by specific bridge (*northbridge* that links the CPU to very high-speed devices, especially main memory and graphics controllers or *southbridge* that connects the motherboard chip to lower-speed peripheral buses; such as Peripheral Component Interconnect (PCI) or Industry Standard Architecture (ISA)). The bridge also has same case of relationship with their motherboard chip in terms of commonality. One of the factors that affect on the performance of this assembly system is the commonality of components among products. Later on, this type of multi-product configuration with multi-function commonality relationship will be wedded as an example. MCC as the proposed strategy is expected to give some useful insights in trading-off ordering cost, inventory holding cost, and material cost.

To compare the new MCC strategy with the previous ones (DP and PCC), we develop a mathematical model to determine the optimal strategy in component commonality and investigate more detail about under what kind of situation that a strategy of component commonality becomes better than the others. A nonlinear programming model for two-segmented-products, multiple layers, and multiple periods inventory model with deterministic demand scenarios is developed to minimize the total inventory related costs, which are material unit cost, ordering cost and inventory holding cost. Sensitivity analysis shows the trades-off of material cost, inventory holding cost, and ordering cost in choosing the best strategy. Parameters setting under certain conditions show the results of appropriate strategy to be applied in each situation.

In brief, we propose a new strategy called MCC that is in between of DP and PCC strategies. To minimise total inventory cost, under three different commonality strategies, a new approach is proposed and the results obtained from mathematical model are expected to be optimal and meaningful. The best chosen strategy among DP, PCC or MCC is reflected by the optimal value of degree of commonality as an important decision variable. In our model, degree of commonality is not only determined for all product family but also per product layer. This means the determined degree of commonality is more detail and accurate compared with previous researches that treat it as parameter for each strategy for the whole product family.

Literature Review

Major decisions in inventory control have concerned with order start times and order quantities. Lot sizing decisions are influenced by numerous factors, such as the demand pattern, raw material availability and cost factors. The trade off in a traditional lot sizing problem is to balance the inventory holding cost and setup cost. If a company decides to avoid the holding cost in every period, it suffers from a high number of setups. On the other hand, inventories have to be carried for many periods (*i.e.* high holding cost) if it procures large amounts to avoid setup costs (Aksen *et al.*, 2003). This finding supports our model in trading off material unit cost, ordering cost, and inventory holding cost related to component commonality utilization.

In recent years, the increasing popularity of mass customization and postponement of product differentiation in manufacturing environments have resulted in new analytical models in areas of component commonality and assembly system.

Component commonality has been studied from various standpoints in the literature. A large portion of research in this area concerned with the impacts of introducing commonality among components on various performance measures in assembly systems (*e.g.*, inventory and service levels, total cost and total profit, *etc.*). Most of the existing analytical models in the inventory control literature were focused on studying the benefits of risk-pooling and order-pooling effect of component commonality on reducing inventory levels and procurement cost solely in relation to the variability of demand (Baker *et al.*, 1986; Gerchak *et al.*, 1988; Eynan and Rosenblatt, 1996; Agrawal and Cohen, 2001, among others). As such, an underlying assumption in all these studies is that the procurement leadtime for components was either zero (negligible) or constant.

The development of mathematical models to study the effects of commonality in the multi-stage systems with multiple products and multiple common components is remained in the virgin area of research. Most research that developed analytical solutions took for granted only one unit of common components were used to assemble a product. Hidayat *et al.* (2009) developed the appropriate supply strategy and technology transfer mechanism for high-technology product, *i.e.* a final or an intermediate product with high technical requirements demanding sophisticated technology and knowledge for its production (*e.g.* vehicles, aircraft, automated or computer-controlled machineries, *etc.*). Based on the findings, we would like to apply the component commonality concept in a high-technology product in ATO system.

There are several definitions related to the terminology of component commonality. Eynan (1996) stated that the commonality is an approach which simplifies the management and control of inventory and also reduces inventory. Meyer and Lehnerd (1997) defined the commonality is a group of related products that share common characteristics, which can be features, components, and/or subsystems. It is a set of subsystems and interfaces that form a common structure from which a stream of derivative products can be efficiently developed and produced. Ma *et al.* (2002) stated that commonality is an approach in manufacturing in which two or more different components for different end-products (or perhaps the same product family) are replaced by a common component that can perform the function of those it replaces. In an ATO manufacturing environment, commonality allows two or more products using the same components in their assembly. In this case, commonality is an integral element of the increasingly popular assemble-to-order strategy that keeps inventory for certain critical components – typically with longer leadtime and more expensive – in a generic form (Mirchandani and Mishra, 2002). In brief, Ashayeri and Selen (2005) summarized that commonality reflects the number of parts/components that are used by more than one end-product, and is determined for all product families.

From the manufacturing point of view, it is a cost-decreasing strategy in a stochastic-demand environment because by pooling risks the total volume of the common components can be forecasted more accurately (Labro, 2004). Wazed *et al.* (2009) studied the commonality indices in manufacturing resource planning reported in literatures since 1980. In their study, it was observed that in designing a new family of products/processes or analysing an existing family, commonality indices can often be us as a starting point. For manufacturing echelon, commonality refers to the parts or sub-assemblies that are shared among different items. For distribution echelons, it refers to the end items that are knitted together or bundled as assortments to customers (Humair and Willems, 2006).

Regarding the value of commonality, Wazed *et al.* (2009) enumerated some indices of commonality; which only considered (0 or 1) or (0 or 100) in determining degree of commonality (those binary variables) in their mathematical models (see Table 1). The disadvantage of this approach is that it pushes the decision maker only to decide either DP or PCC (not considering MCC strategy). By introducing degree of commonality that is not only determined for all product family but also per product layers, the determined degree of commonality will be more detail and accurate.

In our proposed model, we refer to the commonality concept according to the latest research by Humair and Willems (2006) and from manufacturing echelon viewpoint. Degree of commonality itself is defined as a measure of how well the product design utilizes standardized components. A component item is referred for any inventory item (including a raw material), other than an end item, that goes into higher-level items (Dong and Chen, 2005). Subsequently, an end item is a finished product or major subassembly subject to a customer order.

Table 1 The terminology of degree of commonality (in Wazed *et al.* 2009)

Terminology	Abbreviations	Developed by	Commonality Measure for	Degree of Commonality	
				No	Complete
TCCI	Total cost commonality index	Wacker and Treleven (1986)	Whole family	0	100
PCI	Product line commonality index	Kota *et al.* (1998)	Whole family	0	100
CI	Commonality index	Martin and Ishii (1996, 1997)	Whole family	0	100
CMC	Comprehensive metric for commonality	Thevenot and Simpson (2007)	Whole family	0	1
TCCI	Total cost commonality index	Wacker and Treleven (1986)	Whole family	0	100
PCI	Product line commonality index	Kota *et al.* (1998)	Whole family	0	100

According to Kim and Chhajed (2001), in their empirical study of vertical line extensions from both lower-level end-product and higher-level end-product, it was found that the utilization of commonality can increase valuation of the lower-level end-product, but on the other hand, decrease the value of the higher-level end-product. Their research is explored in more detail by Heese and Swaminathan (2006) who developed a stylized model of a manufacturer that offers two products to a market with two segments having different valuations for quality. Enriching their findings, in this research, we propose a mechanism to find the best solution related to both degree of commonality (based on our proposed terminology) and two classes of product valuation concepts.

Model Development

We develop mathematical model in a multi-stage systems with multiple products and multiple common items in deterministic demand situation. We define a new terminology of commonality for each product layer as degree of commonality ($e_{j_u}^{ik}$), which is measured as percentage of unique components j_u in the k^{th} layer of product i produced by using common components.

<u>Model structure</u>

In developing the model, we refer to the product structures as shown in Fig. 1. Later on, we recall the first layer components as parent components and the second layer components as child components.

In Fig. 1, two segmented high-technology products, *i.e.* Intel Pentium PC and Intel Celeron PC, are supported by one motherboard chip as their first layer component. Motherboard chips, as the first layer component, are categorized as motherboard chip that is dedicated for only particular product (later on, it is mentioned as unique component) and motherboard chip that capable to support both products (later on, it is mentioned as common component). Motherboard chip is also supported by a "bridge" as their child component. The "bridges" categorization are the same as their motherboard chip as their parent component. Same logical relationship can be applied in more general cases for different product configurations. According to our example, we index end-products by i, components by j, and layer number by k.

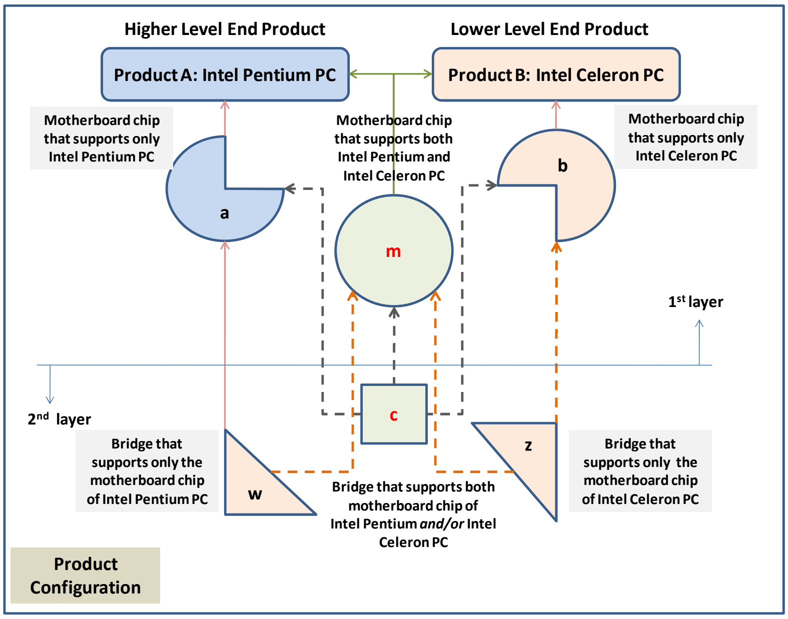


Figure 1 Description of product structure

<u>Model assumptions</u>

In developing the model, we refer to the following assumptions:

1. The product demand during the planning horizon (usually one year) is known and will be continued within times with a constant speed.
2. One unit of component j (either unique component j_{un} or common component j_{com}) in every k layer is necessary to produce one unit of end-product i.
3. Ordering lot size is fixed for every time of order.
4. Ordered parts will be supplied at the same time of order (order leadtime is zero).
5. Price of components are independent to lot size of orders (no discounted price).
6. Ordering cost is fixed for every time of order and inventory cost is equal for the number of components, price of components/unit, and time of holding.
7. There is no production capacity or storage constraint.
8. Child components are supplied altogether with parent components and consumed by lots by each related parent components; the ordering time and number of lots will utilize single cycle time policy.
   - Parent's components demand are constantly derived from product's demand and will be ordered at the beginning of each planning period in one planning horizon and decrease with a constant speed.
   - Lot-for-lot (*L4L*) policy is applied to determine the size of procurement orders for each child component that will be consumed by parent components.

Model notations

We index end-products by i, components by j, and layer number by k. Model notations are defined as shown in Table 2.

Table 2 Notations and definitions of indexes, parameters, variables, and decision variables for product proliferation model

Notations	Meanings
Index	
i	number of end-product being assembled $(i = A, B,...N)$
j	number of component $(j = a,b,m,w,z,c...,n)$
j_{un}	number of unique component $(j_{un} = a,b,w,z,...,n_{un})$
j_{com}	number of common component $(j_{com} = m,c,...,n_{com})$
k	layer number in product configuration $(k = 1,2,...,K)$
$j_{un} \in j_{com} \in j$	
Parameters	
D_i	Annual demand for end-product *i* (unit/year)
P_i^{jk}	Unit price of component *j* in the k^{th} layer of product *i* (\$/unit)
A_i^{jk}	Ordering cost of component *j* in the k^{th} layer of product *i* for every time of order (\$/order)
r	Bank interests (%/year)
Variables	
h_i^{jk}	Unit inventory holding cost per period of component *j* in the k^{th} layer of product *i* (\$/unit year)
q_i^{jk*}	Economic order quantity (EOQ) for component *j* in the k^{th} layer of product *i* (unit/period)
T_i^{jk*}	Optimal period between order of component *j* in the k^{th} layer of product *i*
Decision variables	
$e_{j_u}^{ik}$	Degree of commonality, *i.e.* percentage of unique component j_u in the k^{th} layer of product *i* produced by using common components $\forall i, j_{un}, k$
$Q_{j_u}^{ik}$	Optimal annual order quantity of component *j* in the k^{th} layer of product *i* $\forall i, j, k$

Objective function

To compare the new strategy MCC with the previous ones (DP and PCC), we develop a mathematical model to determine the optimal strategy in component commonality. The focus of this research are inventory related costs, which consists of material unit cost, ordering cost, inventory holding cost, and shortage cost.
The objective function is to minimize all cost elements that are needed to fulfil demand of

products. The cost elements consist of material cost, ordering cost, and holding cost. From the product perspective, all of the total costs involved can be interpreted in Eq. (1).

Minimize Total Cost (TC)

$$TC = \{\text{Material Cost}\} + \{\text{Ordering Cost}\} + \{\text{Inventory Holding Cost}\}$$

$$TC = \sum_{i=1}^{N} D_i P_i + \sum_{i=1}^{N} \frac{A_i}{T_i^*} + \frac{1}{2}\sum_{i=1}^{N} h_i q_i^* = \sum_{i=1}^{N} D_i P_i + \sum_{i=1}^{N} \frac{A_i}{T_i^*} + \frac{1}{2}\sum_{i=1}^{N} h_i T_i^* Q_i \qquad (1)$$

The product itself is produced from the related components (unique components that are dedicated for particular product only and common components which can support all products). In our example, we categorize the components in the product structure as parent components (in the first layer) and child components (in the second layer). In general, all items in layer k^{th} will be the child components of $(k\text{-}1)^{th}$ layer's items, and vice versa. So, components in third layer are the child components of components in the second layer, but become the parent components of components in fourth layer of end-products, and so on.

The need of parent components is derived from the constant demand of product that continues each year. On the other hand, the supply of child components is derived by the *L4L* consumption of parent components that changes within time. These relationships influence the difference in inventory system and pattern for each layer. By breaking down the products structure into components structure composition, we can get Eq. (2). This equation is a general expression that can be applied for all three strategies; DP, PCC, MCC. The difference among strategies depends on the value of degree of commonality, which is one of decision variables in this model. For DP strategy, the value of $e_{j_{un}}^{ik}\ \forall i, j_{un}, k$ is 0 (zero); so it consists only of the total cost resulted from unique components. For PCC strategy, the value of $e_{j_{un}}^{ik}\ \forall i, j_{un}, k$ is 1 (one); so it automatically has only the total cost resulted from common components. For MCC strategy, the value of $e_{j_{un}}^{ik}\ \forall i, j_{un}, k$ is between 0 and 1; so it has both of the total costs resulted from unique and common components.

$$TC = \{\text{Total Cost resulted from Unique Components}\} + \{\text{Total Cost resulted from Common Component}\}$$

$$TC = \{\text{Material Cost}\} + \{\text{Ordering Cost}\} + \{\text{Inventory Holding Cost}\}$$

$$TC_j^{ik} = \left\{ P_{j_u}^{ik}\left(1 - e_{j_{un}}^{ik}\right) D_i + P_{j_{com}}^{ik}\left(\sum e_{j_{un}}^{ik} D_i\right)\right\} + \left\{ \frac{A_{j_{un}}^{ik}\left(1 - e_{j_{un}}^{ik}\right) D_i}{q_{j_{un}}^{ik^*}} + \frac{A_{j_{com}}^{ik}\left(\sum e_{j_{un}}^{ik} D_i\right)}{q_{j_{com}}^{ik^*}} \right\} + \left\{ h_j^{ik} T_j^{ik^*}\left[\frac{Q_j^{ik}}{2}\right]\right\} \qquad (2)$$

for all $i \in N,\ j \in n,\ j_{un} \in n_{un},\ j_{com} \in n_{com},\ k \in K$

In Eq. (2), the first part of first terms of material cost represent the material cost of acquiring unique components a and b (as parent components) and w and z (as child components); while the second part of this terms denotes the material cost of acquiring common components m and c. $(1 - e_{j_{un}}^{ik})$ for $j_{un} = a, b, w, z$ denotes the percentages of demand fulfilled by the replaceable (unique) components, whereas $\left(e_a^{A1} D_A + e_z^{B1} D_B\right)$ and $\left(e_w^{A2} D_A + e_z^{B2} D_B\right)$ are the demand quantity of common components m and c to be ordered.

If all the components are assumed to be outsourced, then the only setup cost is the ordering cost. The long-term average inventory position for part j is $T_j^{ik*}\left[\frac{Q_{jk}^{i}}{2}\right]$ or $\left[\frac{q_{jk}^{i}}{2}\right]$.

Constraints

There are five types of constraints developed in this research.

1. Constraints related to decision variables.

   Value of degree of commonality as a decision variable is between zero and one. Zero means the best strategy should be DP for every product layer, while one means the best strategy should be PCC for every product layer, and the value between them brings MCC, the generalisation of DP and PCC, as the best strategy. This relationship is expressed in Eq. (3).

   $$0 \le e_{j_{un}}^{ik} \le 1, \forall\, i \in N,\, j_{un} \in n_{un}, k \in K \tag{3}$$

   For every chosen strategy, number of component to be attached to products hould be bigger than zero (nonnegativity constraint) as shown in Eq. (4).

   $$Q_j^{ik} \ge 0, \forall\, i \in N,\, j \in n, k \in K \tag{4}$$

2. Constraints related to balance of flows between components' supply and products' demand. Relationship between total procured component and end-product demand is expressed in Eq. (5).

   $$\sum_i \sum_j \sum_k Q_j^{ik} \le \sum_i D_i\,, \forall\, i \in N,\, j \in n, k \in K \tag{5}$$

   Relationship between total ordered child component and the supported parent components is expressed in Eq. (6).

   $$\sum_i \sum_j \sum_k Q_j^{ik} = \sum_i \sum_j \sum_{k=1}^{k-1} Q_j^{ik}\,, \forall i \in N,\, j \in n, k \in K \tag{6}$$

   Relationship between total ordered common component and the supported end-products is expressed in Eq. (7).

   $$D_i\left(1 - e_{j_{un}}^{ik}\right) \le Q_{j_{com}}^{ik}\,, \forall\, i \in N,\, j \in n,\, j_{un} \in n_{un},\, j_{com} \in n_{com}, k \in K \tag{7}$$

   Relationship between total ordered unique component and the supported end-products is expressed in Eq. (8).

   $$\sum_i \sum_{j_{un}} \sum_{k=1}^{k-1} e_{j_{un}}^{ik} D_i = Q_{j_{com}}^{ik}\,, \forall\, i \in N,\, j \in n,\, j_{un} \in n_{un},\, j_{com} \in n_{com}, k \in K \tag{8}$$

3. Constraints related to economic order quantity (EOQ) for every order interval.

   - For unique components

   $$\frac{\partial TC}{\partial Q_{j_{un}}^{ik}} = 0 \rightarrow q_{j_{un}}^{ik*} = \sqrt{\frac{2A_{j_{un}}^{ik}\,(1 - e_{j_{un}}^{ik})D_i}{h_{j_{un}}^{ik}}}\,, \forall\, i \in N,\, j \in n,\, j_{un} \in n_{un}, k \in K \tag{9}$$

   - For common components

   $$\frac{\partial TC}{\partial Q_{j_{com}}^{ik}} = 0 \rightarrow q_{j_{com}}^{ik*} = \sqrt{\frac{2A_{j_{com}}^{ik}\; e_{j_{un}}^{ik}\; D_i}{h_{j_{com}}^{ik}}},\; \forall\, i \in N,\, j \in n,\, j_{com} \in n_{com}, k \in K \tag{10}$$

4. Constraints related to determination of optimal time when orders should be released for each component.

   $$T_j^{ik^*} = \sqrt{\frac{2A_j^{ik}}{h_j^{ik} q_j^{ik^*}}}\,, \forall\, i \in N,\, j \in n, k \in K \tag{11}$$

5. Constraints related to the relationship between component inventory holding cost that is affected by each component price and bank interests.

$$h_j^{ik} = r_j^{ik} \times P_j^{ik}, \; \forall\, i \in N, j \in n, k \in K \qquad (12)$$

Our model structure is categorized as a nonlinear programming (NLP). According to the objective function, the material cost will directly be affected by the degree of commonality value, that is depend on the price per unit of unique and (or) common components. Degree of commonality ($e_{j_{un}}^{ik}$) itself represents the percentage of unique components j_{un} in the k^{th} layer of product i produced by using common components. The composition of material cost is determined after choosing the best strategy, which is related to the optimal value of $e_{j_{un}}^{ik}$. Later on, the composition of product configuration (the necessary materials or components) also affect the inventory holding cost, and ordering cost. The best chosen strategy among DP, PCC or MCC is reflected by the optimal value of $e_{j_{un}}^{ik}$ as an important decision variable. For DP strategy, all resulted value for $e_{j_{un}}^{ik}$ should be 0, which means all product layers utilize unique components; no commonality is applied on the product. On the extreme side, for the PCC strategy, all resulted value for $e_{j_{un}}^{ik}$ should be 1, which means all product layers utilize common components; pure commonality is applied on the product. Between these two extreme situations (no commonality at all or pure commonality), there is MCC strategy that allows flexible alternative values of $e_{j_{un}}^{ik}$ which is between 0 and 1. For deriving solution of the proposed model, we use LINGO 8.0 unlimited software. The applied software is capable to generate global optimum value of degree of commonality.

Basic Numerical Experiments

In order to justify model applicability, some numerical examples for multi-layer product configuration under deterministic demand situation are generated. Referring to product structure in Fig. 1, we employ a set of basic data scenario taken from Johnson and Montgomery (1974) with some additional modified data for the child components as shown in Table 3.

Table 3 Setting data parameters

Parameter	Basic Scenario
r	20%
Demand Product A	20,000
Demand Product B	10,000
Ordering Cost per unit component *a*	70
Ordering Cost per unit component *b*	60
Ordering Cost per unit component *m*	65
Ordering Cost per unit component *w*	20
Ordering Cost per unit component *z*	15
Ordering Cost per unit component *c*	25
Price of component *a*	50

Parameter	Basic Scenario
Price of component *b*	45
Price of component *m*	55
Price of component *w*	30
Price of component *z*	10
Price of component *c*	25

In parameters setting, we assume that higher-level end-product has higher demand than lower-level end-product. Regarding the types of layers, we assume that ordering costs of parent components are higher than those of child components. Furthermore, as with components' types, we assume that the prices of common components should be higher than those of unique components for each layer. This is based on given assumption that those of common components are generally equipped with extended functions such as additional conjunction to attach two different end-products and have to meet the quality standard of the higher-level end-product. This assumption is generated in order to allow trade-off relationship between material, ordering and inventory costs. Material and inventory costs are strongly related with price.

By setting up these parameters values as shown in Table 3, we would like to see the trade-off resulted from material cost, ordering cost, and inventory holding cost and the selected strategies. In fact, our model can be utilized for all cases (more expensive or cheaper price of common components). This is due to the fact that degree of commonality, which determines components quantity is guaranteed to have a global optimum value generated by LINGO 8.0. Furthermore, both cases are considered and analysed in the sensitivity analysis section.

Table 4 Summary of global optimum results by LINGO 8.0

Program Characteristics	LINGO 8.0 (unlimited)	Decision Variables	Value
Model Class	NLP	e_a^{A1}	0.1905061
State	Global Optimum	e_b^{B1}	0.6070251
Infeasibility	0	e_w^{A2}	0.4054410
Iterations	23,830,740	e_z^{B2}	0.5172065
Variables	Total: 16; Nonlinear: 16	Q_a^{A1} (unit/year)	16,189.88
Constraints	Total: 26; Nonlinear: 11	Q_b^{B1} (unit/year)	3,929.75
Nonzeros:	Total: 61; Nonlinear: 36	Q_w^{A2} (unit/year)	11,891.18
Elapsed Runtime (hh:mm:ss)	57:21:50	Q_z^{B2} (unit/year)	4,827.94
Total Cost	**$1,939,600.00 (MCC)**	Q_m^{AB1} (unit/year)	9,880.37
TC of DP is $2,370,771.66	TC of PCC is $2,645,771.66	Q_c^{AB2} (unit/year)	13,280.89

We utilize Eqs. (2) to (12) to get the global optimum solution using LINGO 8.0. According to the global optimum solution, it is shown that the best strategy is MCC. Later on, we try to apply the

PCC and DP strategy in our case in order to compare the resulted total cost and strengthen the global optimum result. The global optimum solution is summarized in Table 4.

According to the basic data scenario, we can see that in certain point, the PCC strategy becomes better than DP strategy (see Fig. 2). It means in some certain values of parameters, there will be a sudden extreme change from DP to PCC or vice versa; or a gradual change via MCC strategy as shown in Fig. 2. In this case, MCC is the interchange strategy between PC and DPP, which achieves the minimum total cost.

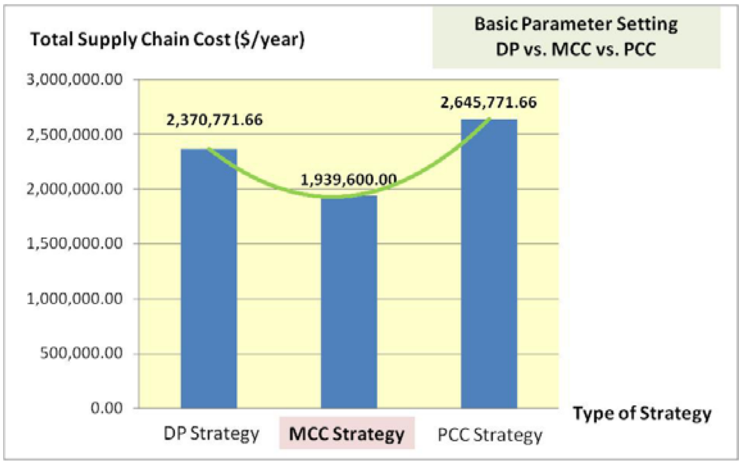


Figure 2 Three strategies comparison by using basic data parameters

By interpreting the global optimum solution (see Table 4), we can get the graphical visualization of product configuration as shown in Fig. 3. Further details in form of tree diagrams are shown in Fig. 4.

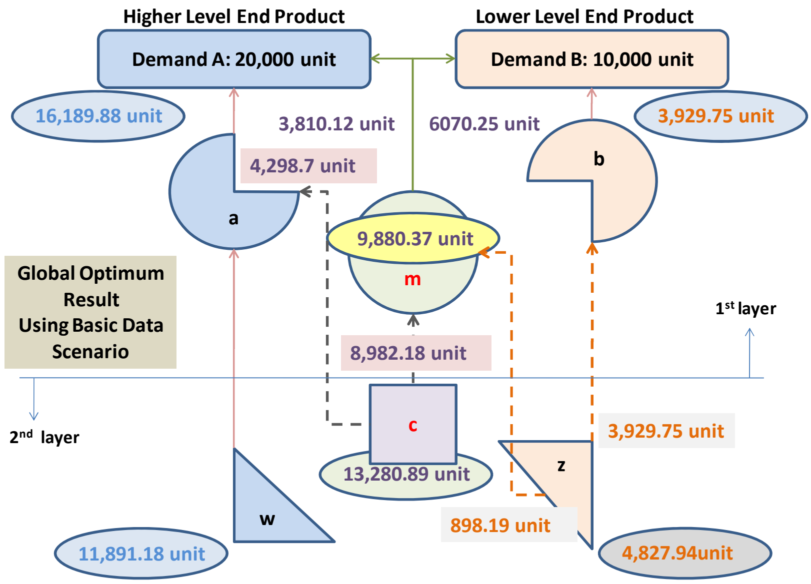


Figure 3 Application of global optimum results to products and components

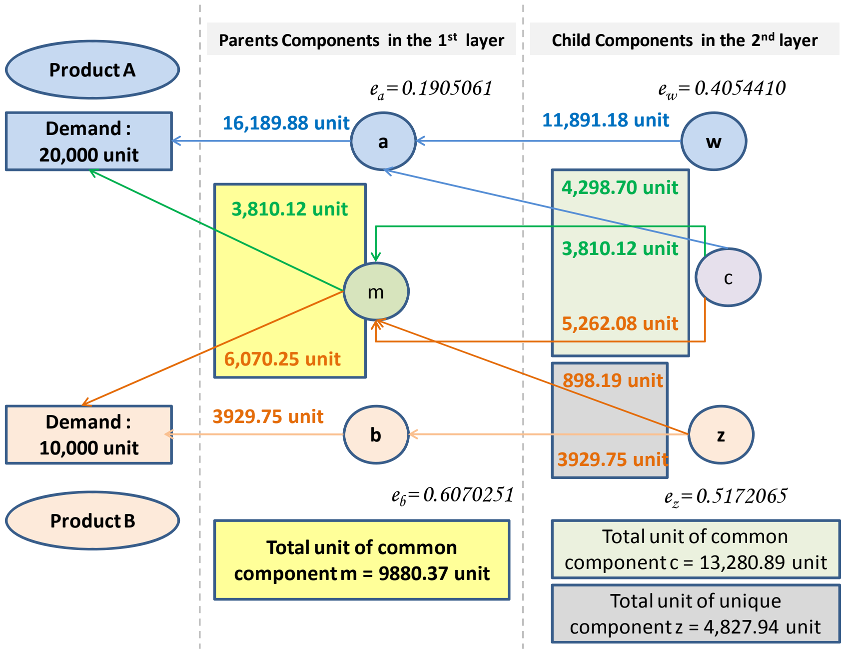


Figure 4 Tree diagram of global optimum solution

Optimum results show that MCC is the best strategy to be applied in all layers of product configuration. From Figs. 3 and 4, we can see that parent component in the first layer of higher-level end-product utilizes only 19% of common component, while for lower-level end-product level utilizes 60.7%. In case of child component in second layer, lower-level end-product utilize 51% of common component, while higher-level end-product utilizes 40.5% of common component. This is due to the facts that total utilization of common components gives more significant benefits in decreasing ordering and inventory costs for lower layer components, compared with slightly higher price of common component.

By utilizing the proposed model, we can get the optimal product composition not only per product layer composition, but also for whole product family. In this case, the significant benefit of MCC strategy can be seen more clearly in a multiple layer product configuration.

Model Analysis

<u>Inventory relationship between parent and child components from the view point of echelon holding stock</u>

We consider a multi echelon serial system with constant demand. Similar with the concept of multi-echelon in Axsater (2000), the inventory relationship between parent and child components in our proposed model utilizes a rule of inventory replenishment of child (in the second layer) to parent components (in the first layer) by using these following assumptions:

1. The *simple serial item*. Item 1 is a final product which is produced from one unit of component 2. It means that item 1 is a product of either Intel Celeron or Intel Pentium PC.
2. Replenishment leadtimes are zero for both parent and child components. Consequently, no differences between inventory levels and inventory positions.

3. The total demand d for parent components derived from end-product demand is constant and continuous.
4. Both items have ordering cost, A_i^{jk} as well as holding cost, h_i^{jk}. Holding cost is related to the interest rate and price of each item. When delivering a batch, the whole quantity is delivered at the same time.
5. No backorders are allowed.
6. The echelon stock of child components is simply the sum of the stock in both installations.
7. For parent components, the echelon stock is equal to the installation stock since there is no downstream stock.

From the point of view of echelon holding stock, the cost borne by the echelon stock must be satisfied in the optimal solution for a two-level system simultaneously. If we consider the structure in Fig. 1, then we can summarize the cost borne by the echelon stock as follows:

$$TC_j^{ik} = TotalCost_{parents\_component} + TotalCost_{child\_component} \quad (13)$$

$$TC_j^{ik} = \left(h_{parents} + (x-1)h_{child}\right)\frac{Q_{parents}}{2} + \left(A_{parents} + \frac{A_{child}}{x}\right)\frac{Demand}{Q_{parents}} \quad (14)$$

Where x is defined as a replenishment index that shows how many time child components are ordered for supporting dedicated parent components in one cycle of end-product demand replenishment.

Alternatively, the total costs can be represented in terms of the echelon stock. Since the echelon stock of child components includes the stock of parent components, the holding cost for parent components should only represent the value added when producing parent components from child components. This means that we shall employ the echelon holding cost as $v_1 = h_{parent} - h_{child}$ and $v_2 = h_{child}$.

$$C_{echelon\_1} = v_1\frac{Q_{parent}}{2} + A_{parent}\frac{Demand}{Q_{parent}} \quad (15)$$

$$C_{echelon\_2} = v_2\frac{xQ_{parent}}{2} + A_{child}\frac{Demand}{xQ_{parent}} \quad (16)$$

$$TC_{echelon} = C_{echelon\_1} + C_{echelon\_2} = (v_1 + xv_2)\frac{Q_{parent}}{2} + \left(A_{parent} + \frac{A_{child}}{x}\right)\frac{Demand}{Q_{parent}} \quad (17)$$

$$Q_{parent} = \sqrt{\frac{2(A_{parent} + \frac{A_{child}}{x})Demand}{v_1 + xv_2}} \quad (18)$$

$$TC_{echelon}{}^2(x) = 2Demand(A_{parent}.v_1 + A_{child}.v_2 + A_{parent}.x.v_2 + \frac{A_{child}.v_1}{x}) \quad (19)$$

$$x = \sqrt{\frac{A_{child}v_1}{A_{parent}v_2}} \quad (20)$$

Proof of Eq. (20) is the derived from these three conditions; *i.e.* (1). If $\frac{A_{parent}}{v_1} > \frac{A_{child}}{v_2}$, then we get $x < 1$; (2) If $\frac{A_{parent}}{v_1} < \frac{A_{child}}{v_2}$, then we get $x > 1$; (3) If $\frac{A_{parent}}{v_1} = \frac{A_{child}}{v_2}$, then we get $x = 1$.

The value of $x = 1$ means that the same batch size for the two items should be applied, and consequently, each time a batch of child components is produced, this batch should immediately be used for production of parent components. This means one particular parent component is supported by one particular child component. This implies that we do not need any stock of child components and our two-stage system can be replaced by a single-stage system.

The condition of $\frac{A_{parent}}{v_1} \geq \frac{A_{child}}{v_2}$ is also sufficient in case of time-varying demand.

Figure 5 below shows the interconnection between multi-echelon inventory replenishment concept with optimal minimum TC concept related to the meeting point between inventory and ordering cost.

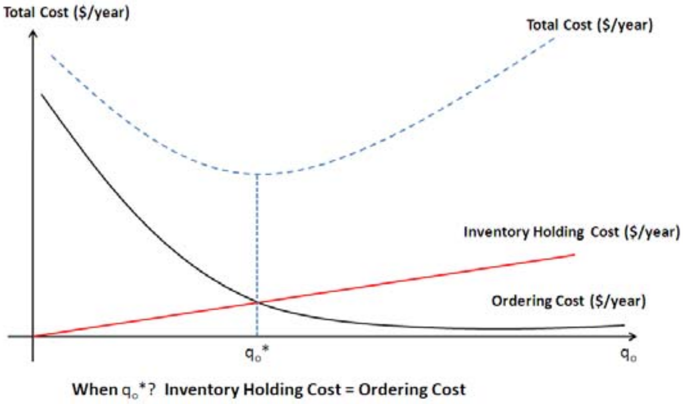


Figure 5 The relationship between resulted TC, inventory holding cost and ordering cost

Given the basic assumption of the annual deterministic demand of end-products, in order to calculate the operating cost, we have to determine the operating stock that includes (1) the economic order quantity (EOQ or q_j^{ik*}) for every order; and (2) the time when it should be ordered (reorder point or T_j^{ik*}). We utilize a single-cycle time policy to guarantee all supporting components for one product will release order or start assembly process simultaneously in two particular time (*i.e.* at the beginning or at the end) of one cycle of planning horizon, as shown in Fig. 6.

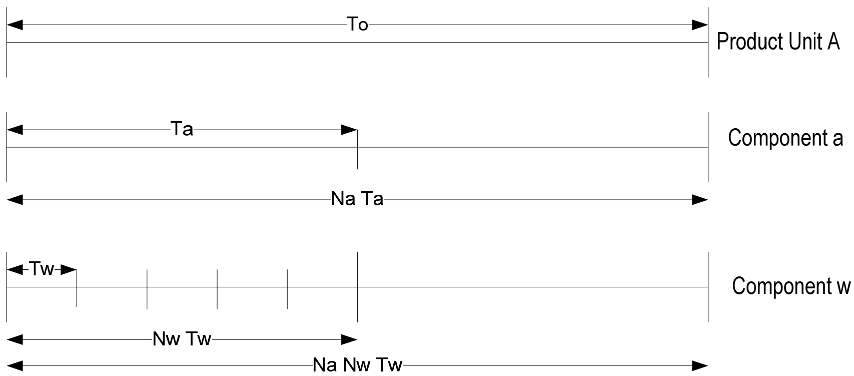


Figure 6 Single-cycle time policy for interconnecting product, parent, and child components (taken into example is end-product *A* in our case, where N_j = *number of component replenishment* and T_j=*replenishment time*)

Referring to single-cycle time policy, in the condition of higher price and longer cycle time of parent components compared to child components $(T_o < T_a < T_w)$, the assembly system itself still can be run. However, if the price of child components is more expensive than the price of parent components, but the cycle time of parent components are still longer, then the cycle time of parent components should be reduced to run the system. This is caused by the inventory waste of parent components under inexistence of child components while waiting to be attached to the end-product. In general, the decision of which kind of parent and child components composition or unique and common components composition that should be chosen depends on the x and $e_{j_{un}}^{ik}$ values (that indicate components allocation and composition). Furthermore, from Eqs. (13) to (19), optimal solutions for operating stock decisions are shown in Table 5 and Fig. 7.

Table 5 Summary of optimum operating stocks results

Com ponent (j)	**Optimal Supply Quantity (Component Supply/ Q_j^{ik})**	**EOQ** (q_j^{ik*})	**Reorder Point** (T_j^{ik*})	**Number of orders in one year**
a	16,189.88 unit/year	1506 unit/order	0.093 (every 34 days)	11 times
b	3,929.75 unit/year	723.86 unit/order	0.184 (every 67 days)	6 times
m	9880.37 unit/year	1081 unit/order	0.109 (every 40 days)	9 times
w	11,891.18 unit/year	• 85.087 unit/ lot size/ order for component *a*	• 2.6154 days (every 62.769 hours)	• 13 times consumption for 1 cycle of component *a*
z	4,827.94 unit/year	• 120.64 unit / lot size /order for component *b* • 16.378 unit / lot size /order for component *m*	• 11.167 days (268 hours) for component *b* • 6.5 days (156 hours) for component *m*	• 6 times consumption for 1 cycle of component *b* and *m*
c	13,280.89 unit/year	• 36.352 unit / lot size/ order for component *a* • 89.339 unit / lot size /order for component *m*	• 3.0909 days (74.182 hours) for component *a* • 3.545 days (85.091 hours) for component *m*	• 11 times consumption for 1 cycle of component *a* and *m*

Visualization of installation stock and echelon stock can be seen in Fig. 7 which shows inventory relationship between parent component b as the first echelon and child component z as the second echelon.

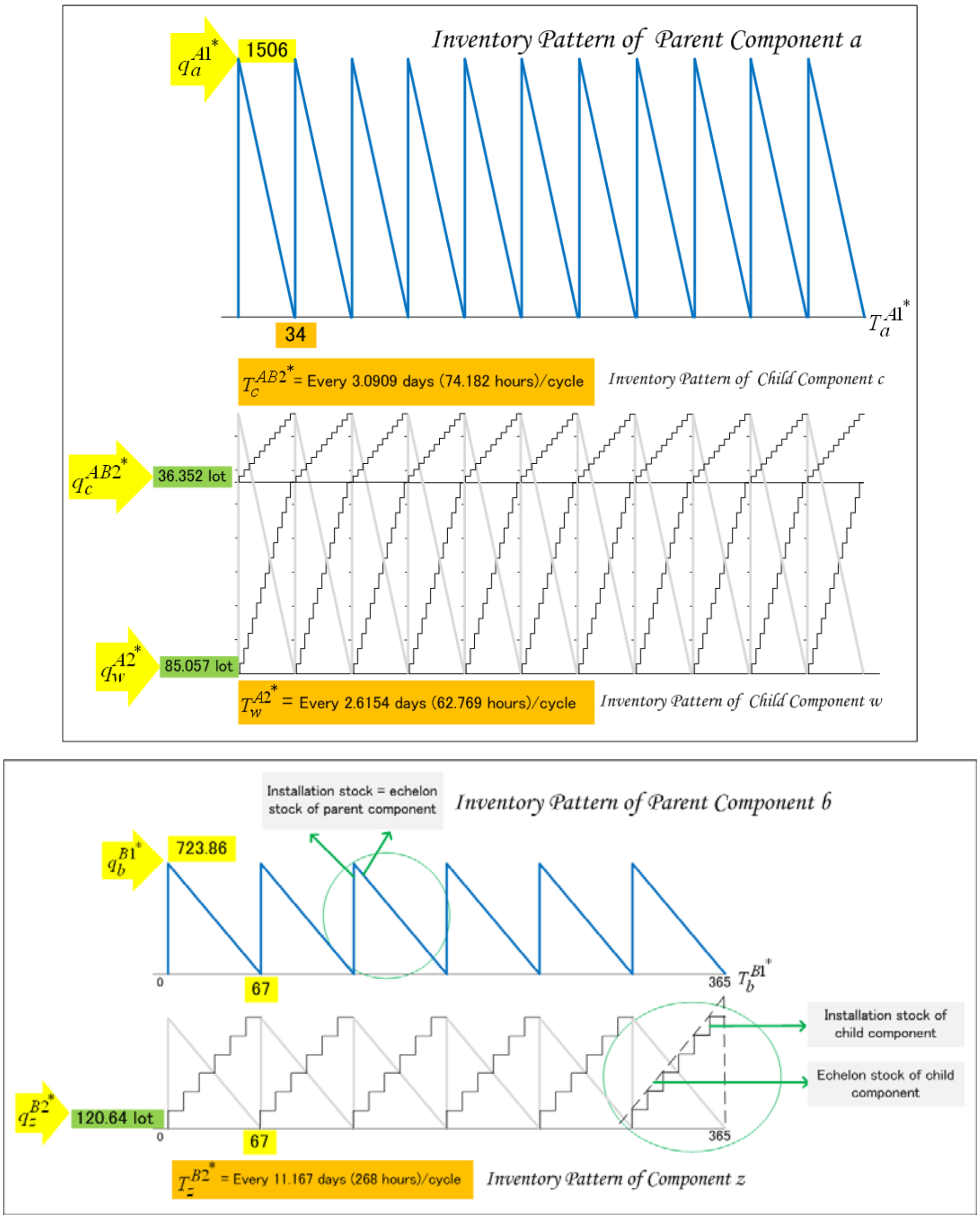


Figure 7(a) Inventory relationship between parent and child components

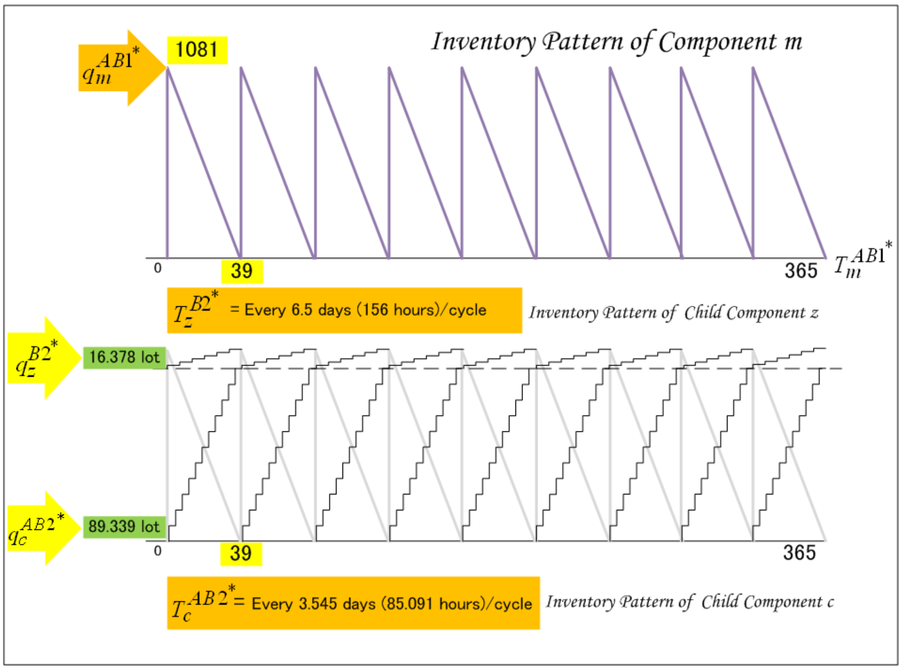


Figure 7(b) Inventory relationship between parent and child components

<u>Strategy comparison in a multi-layer product configuration under deterministic demand</u>

In this section, we would like to explore in more detail the condition where each strategy is more superior to the others. The strategy shifting among the DP, PCC and MCC under certain conditions indicates the existence of interchangeable points of parameters. By undertaking sensitivity analysis, we try to find the border area where the best strategy shifts from one to each other.

Sensitivity analysis from one key parameter point of view

In order to find the appropriate situation in applying each strategy, we then try to apply sensitivity analysis for component price, products demand, and interests rate parameters. While one value of parameter is changed, and the others are fixed, we can get the suitable condition for multi-layer product configuration under deterministic demand situation.

To test the effect of a given factor, first, we decide to investigate the influence of prices of common components upon strategy choise. Fig. 8 shows the price of common component m ranges from $0.00 to $100.00; when the price is between $0.00-$46.00, the best strategy to be applied is PCC; when the price is between $46.01-$55.00, the best strategy to be applied is MCC; and finally when the price is between $55.01-$100.00, the best strategy to be applied is DP.

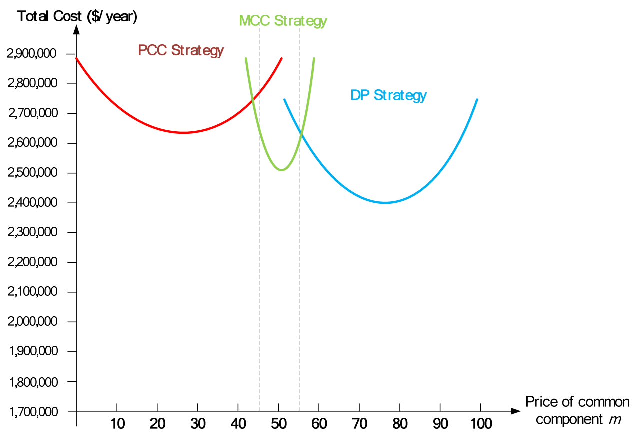


Figure 8 The price of common component *m* effects to the best choice of strategy

Only applying the ranging values of one parameter point of view in a sensitivity analysis cannot get insightful results. Other unusual conditions should be shown for appealing the benefit of the proposed strategy, MCC, in our model. Therefore, we explore in a more detail analysis from two key parameters point of view in the next section.

Sensitivity analysis from two key parameters point of view

In order to investigate in which kind of situation one strategy becomes better than the others, we set the objective function as the function of price of unique component *w* and price of common component *m* as key parameters; while the other parameters are fixed parameters. By considering range of these two parameters from $1/unit to $100/unit, we can get the results as shown in Fig. 9.

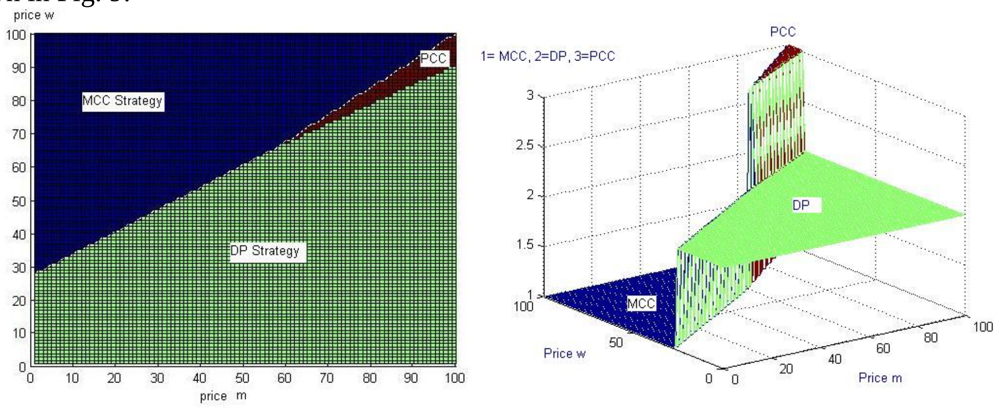
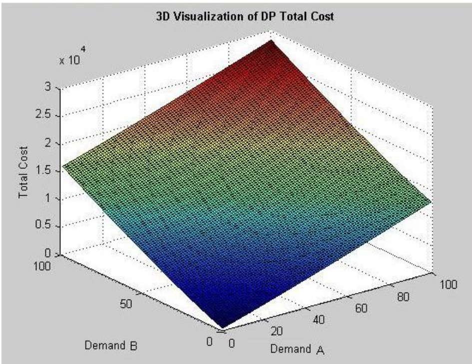
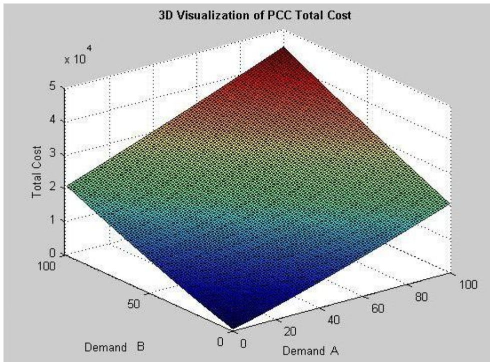


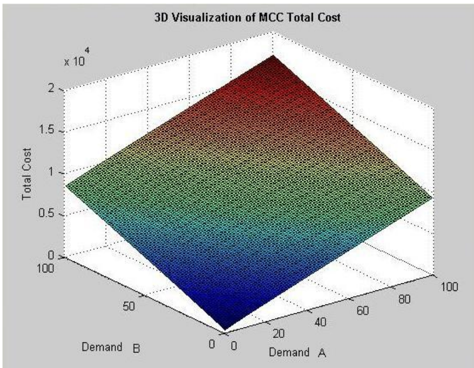
Figure 9 The border area of 2-D area and 3-D visualization under different price of component *m* and price of component *w* setting

By varying prices of common component *m* and unique component *w* simultaneously from $0.00 to $100.00 per unit, we can get 10,000 possible conditions. In each condition, we would like to know which strategy is the superior one (DP, PCC, or MCC). Referring to Fig. 9, DP dominates 60% of area, followed by MCC strategy (33%), and surprisingly, PCC strategy is not preferable. Nevertheless, there are some pitfalls in setting components' price as key parameters. In case of price or ordering cost of components; in DP strategy, the related price and ordering cost of common components cannot be included; and vice versa; in PCC strategy, the related price and ordering cost of unique components cannot be included. In MCC strategy, they are all included. Subsequently, we can only compare between DP and MCC or PCC and MCC. This is not a fair comparison because three of the strategies should be compared simultaneously. The disability in comparing three strategies simultaneously in terms of price as key parameters brings us to choose demand of both products as key parameters to be analyzed. Then, we set the objective function as the function of demand of higher-level end-product A and demand of lower-level end-product B as key parameters; while the other parameters have been fixed. The result in setting these two key parameters is shown in Fig. 10. These two key parameters are chosen because they are involved in all three strategies.

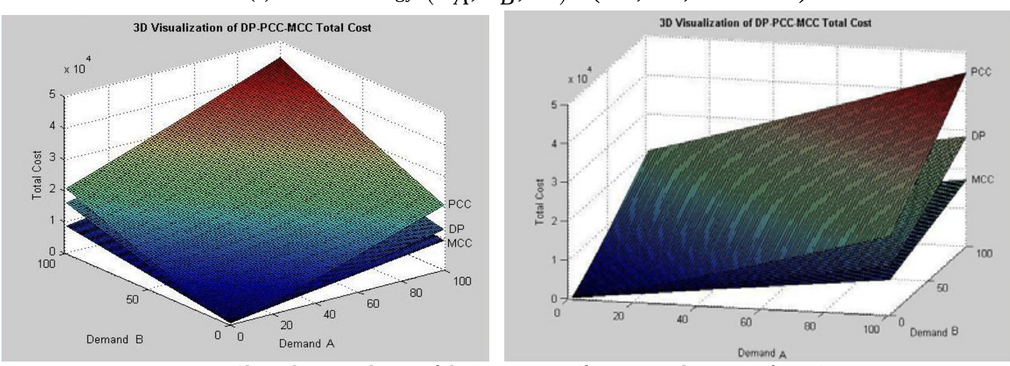




(a) DP Strategy $(D_A, D_B, TC) = (100, 100, 2.82.10^4)$ (b) PCC Strateg $(D_A, D_B, TC) = (100, 100, 4.463.10^4)$



(c) MCC Strategy $(D_A, D_B, TC) = (100, 100, 1.712.10^4)$



(d) The compilation of three strategies (from two sides point of view)

Figure 10 The border area of (a) DP, (b) PCC, (c) MCC and (d) all strategies under different demand A and demand B setting

Referring to Fig. 10, when demand of product A and demand of product B as key parameters are varied from 0 to 100 unit/year, the MCC strategy always becomes the best strategy to be applied. Surprisingly, PCC always becomes the worst compared to the other two strategies. As demands of product A and product B increase, the benefit of MCC becomes significant as shown in Fig. 10 (d), because total cost escalation of MCC is not as steep as DP and PCC. This condition happens when the demand of A (higher-level end-product) decreases, while demand of B (lowerlevel end-product) increases. This means that when demand of higher-level end-product *A* decreases, it is a waste to utilize common components, since the price is more expensive. In this case, it is better for the higher-level end-product to choose MCC strategy; while the lower-level end-product should employ DP strategy. In general, the significant drop in higher market product induces the benefit of MCC. PCC strategy will be beneficial if the price of common components has a slightly significant difference (higher or lower) from unique components.

The derivation of alternatives of product structures

There are 25 alternatives of product structures (variants) in multiple layers product configuration with particular relationship between common and unique components as shown Fig. 1. The first two of the variants are the extreme ones, *i.e.* DP and PCC. The rest 23 variants are the combinations of MCC structures. When selecting the best strategy under parameter setting condition, a general rule is applied. First, we select the best MCC variant that gives the minimum total cost and after that, we compare the selected one with DP and PCC strategy. For practical situation, by utilizing our model, a company can define how many product structures combination (variants) are optimal to be produced within some budget limitation.

By utilizing Eqs. (1) to (12) to each possibility of product structure, we can get the results shown in Figs. 11 to 13 by changing the interests rate value, demand of product and price of components.

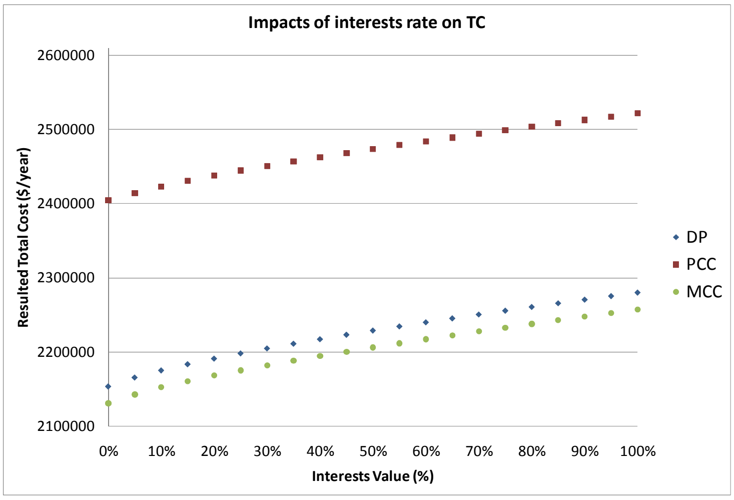
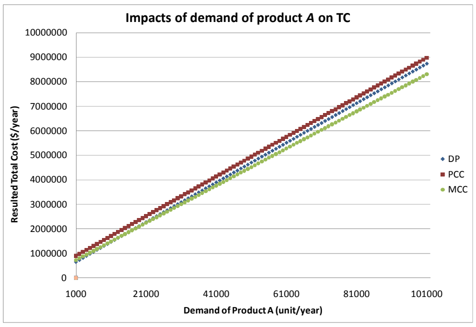
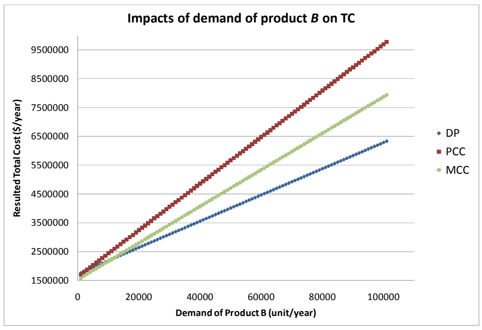


Figure 11 Total cost and ranking (preference) of product structure (Interests value is ranging from 0% to 100%)

According to Fig. 11, for any value of interest rate, MCC strategy, which produces components *a*, *b*, *c*, and *z*, is always superior to DP and PCC strategies. It is followed by DP and finally PCC strategy. This result indicates that interest value is not a sensitive parameter.



(a) Demand for product *A*



(b) Demand for product *B*

Figure 12 Total cost and ranking (preference) of product structure (Demand of product A and B are ranging from 0 to 101,000 unit/year)

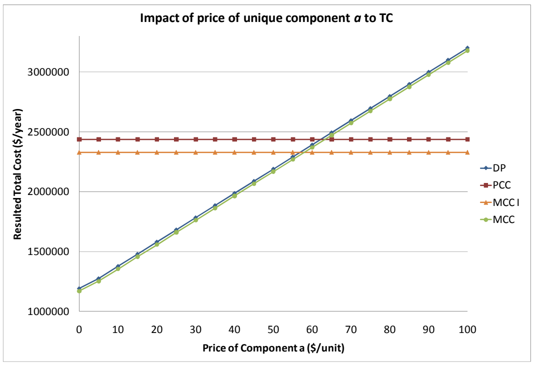
Next, in the sensitivity analysis where demand of product A and demand of product B are chosen as key parameters and ranged from 0 to100 unit/year to compare DP, PCC, and MCC simultaneously, the ranking of best strategies are (1) MCC in which components *a*, *b*, *c*, and *z* are produced; (2) DP; (3) PCC. For higher-level end-product A, in low demand situation, DP strategy is preferable. However, in higher demand situation, MCC strategy becomes the best strategy. In contrary, PCC strategy will never be beneficial for higher-level end-product. This means that for the decreasing demand of higher-level end-product, the use of common components becomes a waste.

Referring to Fig 12(b), in case of lower-level end-product B, in low demand situation, MCC strategy is preferable. Nevertheless, in higher demand situation, DP strategy becomes the best strategy because the saving from unique components material cost is greater than its expenditure for inventory and ordering costs. In general, it is better for higher-level end-product A to utilize MCC strategy and for lower-level end-product B to utilize DP strategy.

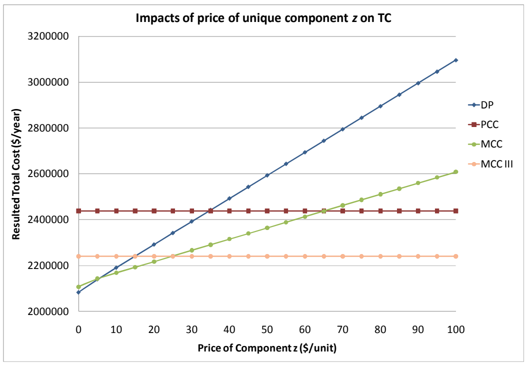
Unlike undertaking sensitivity analysis from two key parameters point of view, in investigating the impact of price to product structure preference, we do not find any pitfalls in setting any of component prices as key parameters. As shown in Fig. 13, the impact to TC can be shown as a constant result even if there is any component price that has no relation with any of the strategies.

Given the price is a sensitive parameter; in a multi-layer product structure, the PCC strategy is rarely selected for the total product configuration. If common component is utilized, it is only for single-layer product as seen in Fig. 13 (e). This is due to the fact that higher price of common components as compared to the unique ones affects the inventory cost significantly. If the price is more dominant than ordering cost itself, when the bank interest is high (that later on will impact the inventory holding cost), we find that the MCC strategy can be utilized to encounter PCC pitfalls by reducing inventory cost. These all findings are indicated in Fig. 13.

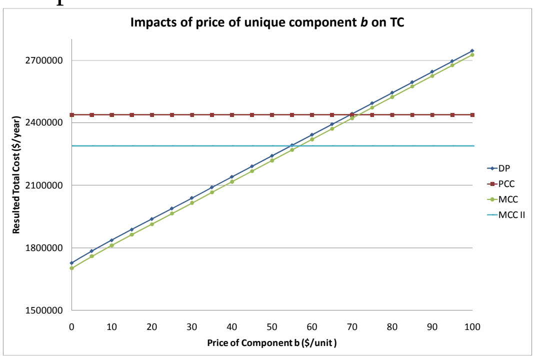
Referring to Figs. 13(c) and 13(f), DP strategy is more preferable than PCC strategy in the condition where the price of second layer of common component is more expensive than the price of second layer of unique component of lower-level end-product. This finding is strongly related to our single-cycle time policy. If the price of child components is more expensive than the price of parent components, but the cycle time of parent components are still higher, then the cycle time of parent components should be reduced to run the system. This is caused by the inventory waste of parent components under inexistence of child components while waiting to be attached to the end-product.



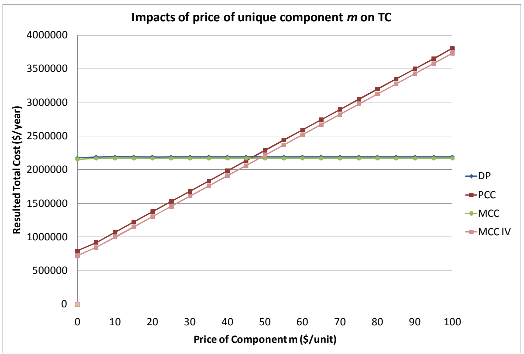
(a) Price of unique component *a*



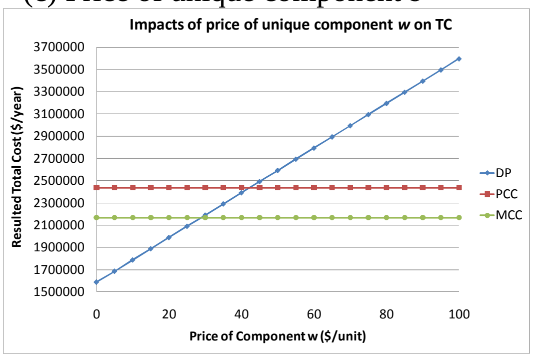
(b) Price of unique component *z*



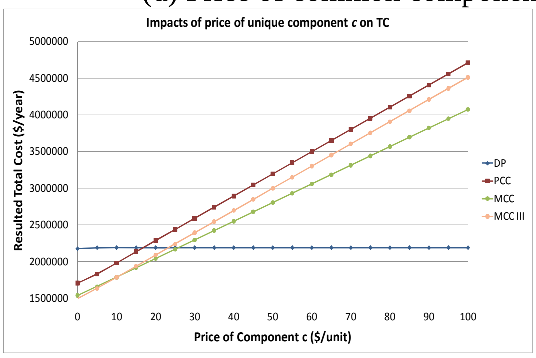
(c) Price of unique component *b*



(d) Price of common component *m*



(e) Price of unique component *w*



(f) Price of common component *c*

Figure 13 Total cost and ranking (preference) of product structure (Price of components are ranging from $0 to 100/unit)

Moreover, in most of parameter conditions, MCC always becomes superior in overall product configuration (see Figs. 13(a), 13(b), and 13(e)). This is due to the ability in facilitating commonality by mix-and-matching unique vs. common components of parent and child components in a multi-layer product configuration, altogether with the success of reducing total cost. The detail summary of Figs. 11 to 13 is recapitulated in Table 6. The strategy shifting are indicated by the highlighted letters of components in the second column of Table 6.

Table 6 Strategy shifting and intersection area when a strategy becomes better than the others

Sensitive parameter	Interchange point of parameter value (1) and best strategy to be applied (2)	Interchange point of parameter value (1) and best strategy to be applied (2)	Analysis
Price of unique component *a* (parent component of higher-level end-product A) in Fig. 13 (a)	**(1) $0-$55 / unit** **(2)** MCC (***a*,** *b*, *c*, *z*) Followed by DP	**(1) $56-$100/unit** (2) MCC (***m*,** *b*, *c*, *z*) Followed by PCC	For both cases, when the price of unique parent-components exceed the price of common parent-component, the 1st layer tend to utilize common component (therefore ***a*** and ***b*** shift into ***m***). In the 2nd layer of child components, MCC strategy is still preferable. In overall product configuration, MCC strategy is always be superior to the others.
Price of unique component *b* (parent component of lower-level end-product B) in Fig. 13 (b)	**(1) $0-$55 / unit** (2) MCC (*a*, ***b*,** *c*, *z*) Followed by DP	**(1) $56-$100/unit** (2) MCC (***m*,** *a*, *c*, *z*) Followed by PCC	
Price of unique component *w* (child component of higher-level end-product A) in Fig. 13 (c)	**(1) $0-$25 / unit** (2) DP (*a*, *b*, ***w*,** *z*)	**(1) $26-$100 / unit** (2) MCC (*a*, *b*, ***c***, *z*)	In case of higher-level end-product A, when the price of unique child-component *w* exceeds the price of common child-component *c*, the strategy domination shifts from DP to MCC. In this case, the existence of unique component ***w*** is replaced by common component ***c***.
Price of unique component *z* (child component of lower-level end-product B) in Fig. 13 (d)	**(1) $0-$5/ unit** (2) DP (*a*, *b*, ***w***, *z*) 1st MCC changing: **(1) $6-$25/unit** (2) MCC (*a*, *b*, ***c***, *z*)	2nd MCC changing: **(1) $26-$100/unit** (2) MCC (*a*, *b*, *c*) ➔ *z* is eliminated	In case of lower-level end-product B, DP strategy is only chosen in a very low price of unique component *z*. Otherwise, MCC strategy is more preferable. There are two-times of MCC strategy shifts just *before* and *after* the price of unique child-component exceed the price of common child-component.
Price of common component *m* (common parent-component) in Fig. 13 (e)	**(1) $0-$45/unit** (2) MCC (***m***, *c*, *z*) Followed by PCC	**(1) $46-$100/unit** (2) MCC (***a*, *b***, *c*, *z*) Followed by DP	When the price of 1st layer of common component is less than the price of 1st layer of unique components of lower-level end-product B, the layer will utilize common component for both products. On the other hand, when the price of 1st layer of common component is more expensive than the price of 1st layer of unique components of lower-level end-product B, the layer will utilize unique components for both products. For both conditions, in the 2nd layer of child components, MCC strategy is still preferable by utilizing both common and unique components. In overall product configuration, MCC strategy is always be superior then the others.
Price of unique component *c* (common child-component) in Fig. 13 (f)	**(1) $0-10/unit** (2) MCC (*a*, *b*, *c*) **(1) $11-$25/unit** (2) MCC (*a*, *b*, ***c***, ***z***)	**(1) $26-$100/unit** (2) DP (*a*, *b*, ***w***, *z*)	When the price of 2nd layer of common component is less than the price of 2nd layer of unique components of lower-level end-product B, MCC strategy is still preferable in two shifts. On the other hand, when the price of 2nd layer of common components is more expensive than the price of 2nd layer of unique components of lower-level end-product B, DP strategy becomes superior.

The best selected alternatives of product variants according to sensitivity analysis results is shown in Fig. 14.

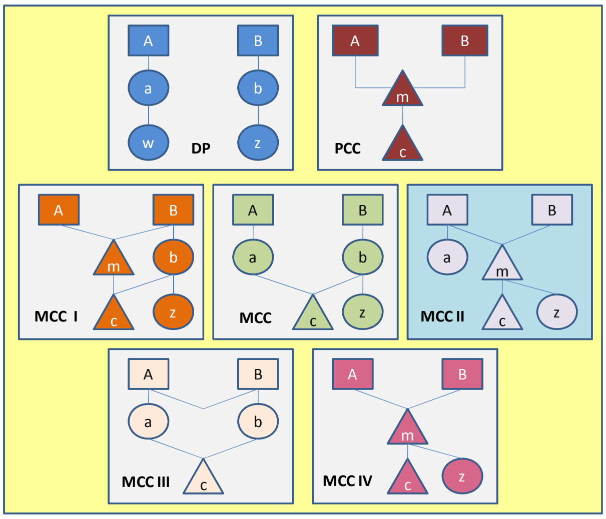


Figure 14 The best-seven variants of product configuration resulted from sensitivity analysis

The merits and demerits of utilizing the DP, PCC, and MCC strategies are summarized in Table 7.

Table 7 Summary of DP, PCC, and MCC strategies

	Merits	Demerits
DP	• Easy to manage in the condition of low ordering cost of unique components. • Suitable for singe-layer product structure with lower price of unique components compared to common components.	• Higher inventory level. • Not suitable for lower price of common parts for many cases. • High dependency to the supplier. • Longer customer waiting time, lower customer service level.
PCC	• Resulting lower inventory level in single layer but not in average total inventory per period. • Suitable if the ordering cost of unique components is high. • A cheaper common component in single-layer product for many cases is suitable to be applied. • Easier demand forecasting.	• Not suitable for higher price of common components. • Can cover only one layer of product configuration. • Unable to achieve the global optimum solution that minimizes inventory cost in some particular point on high demand variation.
MCC	• Beneficial in ATO system because it will allow two or more products using the same components in their assembly (shown in “the derivation of alternatives of product structures” section). • Balancing between inventory, ordering, and material cost. • Beneficial to reduce inventory cost in high inventory holding cost that is reflected by bank interest (shown in Fig. 11). • Adaptable for either customized products or non-customized products (because of two layers product configuration existence). • Beneficial to reduce total cost with the ability in facilitating commonality by mix-and-matching unique vs. common components of parent and child components in a multi-layer product configuration.	• Most difficult demand forecasting. • Needs supports of high-integrated information system.

Conclusions

We propose a new strategy called Mixed Component Commonality (MCC) that is a generalisation of Distinctive Parts (DP) and Pure Component Commonality (PCC) strategies. We have developed a mathematical model considering DP, PCC, and MCC strategies that are integrated into one objective function under deterministic demand and multi-layer product configuration. In minimising the total cost, under three different commonality strategies, the mathematical models are analyzed and the results obtained by LINGO 8.0 are meaningful. The solution to minimizing the total inventory cost is presented and the managerial insights are derived from our analysis.

We find that under deterministic demand and multi-layer product situation, the MCC strategy is significantly beneficial to be applied. In most cases from the previous research, service level of product with commonality is higher than without commonality. However, according to our finding in the sensitivity analysis, in a multi-layer product structure, by trading-off material cost, inventory holding cost, and ordering cost in choosing the best strategy, the PCC fails to decrease the average total inventory cost of products per period. Due to the fact that the price of common components is more dominant than ordering cost itself, especially when the bank interests is high (that later on affects the inventory holding cost), we find that the MCC strategy can be utilized to encounter PCC pitfalls in reducing inventory cost.

In contrast, DP strategy is more preferable than PCC strategy in the condition when the price of second layer of common components is more expensive than the price of second layer of unique components of lower-level end-product. This finding is strongly related to our single-cycle time policy.

As expected, MCC becomes superior to DPP and PCC in ATO system of high-technology-product structure, when the price of common components is relatively higher than unique components, but ordering cost is significantly lower. Moreover, in most of parameter settings, MCC always becomes superior in overall product layers. This is due to the ability in facilitating commonality by mix-and-matching unique vs. common components of parent and child components in a multi-layer product configuration, together with the success of reducing total cost.

For practical situation, by using our model, a company can decide the degree of product differentiation (how many product variants can be produced; shown by degree of commonality value) with the specific budget allocation. Based on this purpose, we are going to determine all possible product variants into one mapping area under the setting of key parameters in order to find the border or area or intersection of each strategy in more details.

Our future research will be extended into the multiple supplier problems, in which each supplier has different components' supply function based on dynamic pricing concept, to examine the impact of product proliferation in vendor selection. Later on, we will develop model integration of component commonality and dynamic pricing in supplier selection problem.

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Towards A Systems-Based Approach to Inform A Capability Decision

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Abstract

When choosing between capability options, the Department of Defence faces a complex array of factors that influence the decision. These factors include a number of quantitative and qualitative assessments reflecting the diverse range of applications, environments and operators involved in the potential application of the capability. Current evaluations focus on rating/weighting techniques with a view to identifying maximum compliance with quantitative-based criteria. Acquisition decisions are often based on evaluations of equipment against engineering criteria and have usually not considered the impact of a new component on the whole system performance. This paper explores the application of the Systemic Intervention Methodology and the System Instantiation Comparison Method to the evaluation of system options. The systems-based approach provides a valid framework for the evaluation.

Keywords: Defence, Mathematical Programming

Introduction

The Australian Department of Defence maintains a program to ensure that the equipment that it issues to soldiers continues to allow them to undertake the tasks required of them and to protect them from harm in changing environments. This involves the integration of different equipment from a number of sources with the trained soldier to create the soldier combat system. The evaluation of options and selection of combinations of equipment to generate soldier combat capability is not a trivial exercise: a number of inter-related and independent systemic and individual performance factors need to be identified and assessed. The soldier combat capability system is defined in terms of sub-systems which may be acquired independently over different timeframes then integrated with the soldier to form the complete system.

Soldiers are required to undertake a variety of tasks in different locations, under different climates and in different team constructs. As a result of this variability, no military mission is perfectly repeatable and, consequently, individual soldier skills need to be applied in a variety of ways. At the lowest level, a number of representative generic actions have been identified as the basis for the assessment of the impact of each sub-system and combination of equipment on individual soldier performance. To compound the analysis, individual soldier performance can be defined differently according to the perspective taken by the analyst or decision maker. Further, soldiers are rarely employed as individuals but work as part of a small team. Consequently, recent research into performance evaluation has been based on small teams rather than individual soldier skills and the impact of different combinations of sub-systems on the performance of specific skills (Hobbs and Chalmers, 2003). The approach adopted in this study seeks to assess the impact of new equipment on the performance of basic essential skills by soldiers to generate the desired effect required by each individual mission.

Historically, new equipment has been selected according to the value for money each option presents against a series of engineering performance criteria. The impact each option has on system performance. It is possible that not all effects will manifest themselves as variations in performance of given tasks with some issues being identified through qualitative analysis. A systems-based approach is being explored to better inform capability option decisions.

This paper presents the application of a systems-based approach to inform the decision maker about selection of soldier combat capability.

Methodology Overview

The challenge for the case study is to identify the system elements rather than evaluate specific equipment solutions. Here the challenge is to identify a method to identify and aggregate ratings against agreed system attributes for each element of the soldier combat system. Consequently, system definition and recognition of the need for different techniques appropriate to various aspects of the system are critical elements of the analysis process. To meet this need, the overarching methodology adopted was Midgley's Systemic Intervention Methodology (Midgley, 2000). The methodology supports a systems view, an iterative approach and the integration of tools appropriate to each phase of the analysis. The methodology identifies three foci – boundary critique, judgement and action. The methodology provides for the three areas to be undertaken in an iterative manner so that earlier phases can be revisited should additional information arise in subsequent considerations. The conventional starting point is to develop an understanding of the nature and scope of the problem under consideration through a boundary critique.

The boundary critique seeks to establish the boundaries of the subject of the analysis – in this case the elements of the soldier combat system capability to be included. Equally importantly, the boundary decision identifies elements of the system that would not be included and interface issues that might need to be considered. Once the problem is agreed, appropriate analysis tools and techniques can be identified.

The judgement phase provides for the selection of theories, tools, techniques and measures suitable for the purpose of the analysis of the problem at hand. In this case study, the problem requires the methods chosen or developed to provide an ability to incorporate comparisons of competing soldier close combat equipment options empirically and to utilise military subject matter expertise. The qualitative aspects of the method provide for an interactive approach that could inform issues for detailed exploration under other technically-focussed perspectives such as human factors performance and equipment engineering performance. For this analysis, a range of techniques, including multi-criteria strategies, SICM, experiment style activities and qualitative tools are appropriate to gather the empirical and qualitative data needed to inform the decision.

The third phase of the methodology, action, is the implementation of the agreed activities and monitoring of results. In this case study, the action is the conduct of the data gathering activities and the analysis of results in order to inform decision makers and others as necessary. Also, this case study is a pilot that will inform the design and conduct of future similar activities.

Boundary Critique – Defining the System

This section discusses the determination of the system boundary and linkages to external systems as applied to the soldier combat system. A number of authors inform discussion about definition and measurement of soldier systems and the tasks required of them.

Previous studies highlighted challenges associated with defining the soldier combat system (Curtis et al, (2006), Rees and Bowden (2007) and Rees and Stanton (2008)) and incorporated decomposition and task analysis methods (Chow et al, (2006)). Most tended to focus on specific aspects of the system as appropriate to the problem they addressed. Hobbs and Chalmers (2003) undertook a collation of a number of these studies including Curtis (1994), Curtis and Dortmans (2003), Curtis and Hobbs (1997), Hobbs and Nicholson (1999), and Hobbs and Curtis (1998). They showed that the work for comparing capability options evolved over time. Initially, methods concentrated on the individual dismounted combat soldier, with later studies treating this system as a component of a larger system, eg section, platoon or company. Thus the emphasis changed to developing methods for the analysis of small units rather than specifically the individual soldier.

Hobbs and Chalmers (2003) indicate that the soldier combat system was found to be too complex a system for meaningful analysis as a singly defined entity. To overcome this problem, the system was divided into infantry tasks, and then into combat activities. These were further broken down into smaller components to derive skills used repeatedly and add value to the capability of soldiers to perform their tasks. In summary, the functionality of the soldier combat system is characterised in terms of generic activities and core skills required of a soldier. Other variables that impact on the soldier combat system can be grouped into the areas of human performance, technology, standard operating procedures and doctrine, training and environment. In these studies, the broad foundational areas of survivability, mobility, sustainment, protection, lethality and Command, Control, Communication, Computers and Intelligence (C4I) originally promoted by the North Atlantic Treaty Organisation (NATO) were rejected as a foundation for the analysis process. Hobbs and Chalmers (2003) highlight that, whilst these functions describe the system they do not provide a suitable framework or structure of meaningful military tasks for analysis or observation. The challenge for this case study is to work through and around these paradigms to identify the system elements relevant to the decision being informed – the selection of future capability options.

Related reviews (Rees et al, 2008) and military subject matter experts highlight combat load, agility and ergonomics as areas of consideration when selecting equipment. Well established methods and tools are available for the measurement of performance of equipment options against defined weight, ergonomic and human factors attributes. Most of these approaches involve measures of performance as defined by Curtis and Bowley (1999) rather than measures of effectiveness or measures of capability. An area not commonly assessed is the impact of combinations of equipment on soldier skills. The problem statements have usually focussed on perspectives such as improving protection from small arms fire. These perspectives continue to be relevant to the selection of equipment, consequently, the tools and methods developed will need to recognise these perspectives and seek to inform input from established specialist evaluations as part of system of systems evaluation. This case study, however, seeks a holistic approach that is based initially on the soldiers' ability to do their job.

A major challenge in determining the system in this case was the many perspectives and definitions as to the nature of a soldier's "job". Soldiers need to be prepared to undertake a variety of tasks to achieve any of a number of goals. To do this, they are trained to perform a number of basic skills to provide them a toolbox from which they choose and combine skills according to the task, threat and environment. Soldiers also work in many specialities and trades including mechanic, artillery gunnery, storeman and driver.

Regardless of their trade, all soldiers are trained to a base level of combat so that they can protect themselves and others in the area of operations. Further, the primary purpose for acquiring the desired equipment under the soldier combat capability system is to enhance the capability of the soldiers applying close combat skills – the base skills in which all soldiers are trained. Consequently, the evaluation will focus on the impact of equipment on these basic skills. Impact on non-combat trades and issues of equipment measures of performance are outside of the boundary of this initial case study. This leads us to the challenge of describing the system.

NATO has identified five sub-systems that make up the close combat soldier capability - Survivability, Sustainability, Lethality, Mobility and C4I. The division of equipment acquisition tends to follow this framework. The assessment of impact on soldier performance can also apply this framework but not universally. For example, the acquisition of body armour provides protection but can also affect the performance of individual skills. Also, when acquisition focuses on single sub-systems, there is the possibility that different combinations of equipment will interact differently to reduce the effectiveness of soldier performance. Recent lessons from operations have highlighted some concerns that buying new equipment has reduced the effectiveness of or generated a need to modify other equipment. The focus of this case study is to develop an approach to inform the assessment of options based on the effect of the complete system of proposed equipment on soldier performance. The evaluation of, for example, the body armour's ability to stop bullets, its weight and fit remain relevant to the decision but these need to be considered in light of the impact the option has on the soldier's ability to shoot, survive, be sustained and to communicate.

The scope of this test, then, will be the ability of the soldier to perform the basic actions required of them under the base sub-systems of lethality (ability to shoot) and agility (the ability to move through varied terrain). The selection of these sub-systems is driven in part by the availability of equipment for the pilot study and in part by the recognition that these requirements are common to all soldiers and most likely to be affected by variations in equipment.

Judgement Phase

The analysis seeks to assess the impact of equipment on performance of individual enabling soldier skills. The assessment seeks to select activities that will test the effect of the equipment on the performance of basic skills in the areas of lethality and mobility. Another aspect of the problem space is that it is not purely empirical, but lends itself to incorporation of the qualitative richness of subject matter expert insights arising from the performance of tests. It is focused on the decision-maker's purpose; in this case to determine the effect of combinations of equipment on the performance of basic agility and lethality skills and actions.

System Instantiation Comparison Method

The System Instantiation Comparison Method (SICM) as described by Rees and Bowden (2007) provides a suitable evaluation framework that focuses on the fundamental effects or functions of a system regardless of context or scenario. The method's strengths include ability to cope with qualitative and quantitative data; flexibility in application; and the use of various mathematical models suitable to the study. The technique incorporates the qualitative richness of subject matter expert insights arising from the conduct of the tests. The flexibility of the technique is in not dictating a mathematical model but allowing for the use of a model appropriate to the study. Williams et al (2001) discusses a mathematical model for use when applying SICM. The technique is similar to a multi-attribute rating in that it seeks to produce a single score for each instantiation based on the decision-maker's preferences and the test results.

The SICM model, shown in Figure 1, and described in detail by Rees and Bowden (2007), consists of three central elements: the critical component, the system functions and the system enablers. The operational requirement or purpose of the system determines the critical components and system functions; these elements are static across all instantiations of the system being compared. The system enablers are the part of the system that vary between different instantiations and define how the system functions operate on the critical components to achieve the operational requirements.

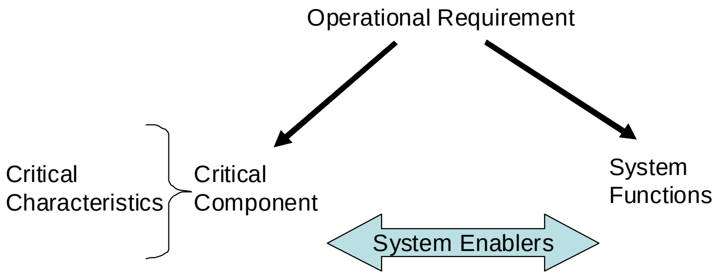

Figure 1 System Representation Using System Instantiation Comparison Method

While Figure 2 highlights a holistic view of the soldier system, the equipment under consideration for this case study will affect the skills that contribute to individual soldier combat system represented as lethality and mobility. The assessment seeks to select activities that will test the effect of the equipment on the performance of basic skills in these areas. In this case study, the dynamic system enablers are the technologies inserted into the soldier system capability platform (the individual soldier). Instantiations are different combinations of equipment in the soldier combat capability system. Each instantiation is then tested with performance being measured and comparisons drawn across instantiations.

Figure 2 System Instantiation Comparison Method View of Individual Close Combat Soldier System

In order to generate measurable responses for use in the analysis and to determine the effect of different equipment and combinations of equipment, physical trials were used. A randomised complete block design activity-based experiment was used to generate data on each instantiation with the basic skills expected of the soldier will influence the selection of the activities. Statistical analysis of variance will be undertaken to explore the effect of different equipment on soldier performance and the interaction between different combinations of equipment. A number of statistical packages are available to support this analysis; the authors chose R due to recent familiarity and availability of the package.

Some system effects may not manifest themselves in changes in measured performance. For example, some participants may experience difficulties in achieving the same response for an activity. Survey and interview tools were developed to capture such issues and to identify conduct issues for future activities. The application of SICM to this case study depicts the grouping of both qualitative and quantitative data against instantiation.

Design of Data Elicitation Activities

Skills specifically related to equipment are usually measured as part of the acquisition of that equipment but such tests may not incorporate consideration of effect on basic skills. Initial analysis of the range of basic soldier skills (Rees and Swift, (2008), and Rees et. al (2008)) suggests that most of the basic soldier skills that are not based on the equipment represent the ability of the soldier to fire a weapon and to move around the battlefield. Therefore, participants are submitted to a combination of shooting and agility tasks based on basic military training requirements. The test activities are drawn from shooting tests and obstacle courses representing the range of movements and skills in which soldiers need to be proficient. The equipment is not the only factor that will influence participants' performance during the activities.

As a pilot activity to inform the analysis, the sub-systems of 'lethality' and 'mobility' were selected as the focus of the test. The tests identified as representing the common core skills of the soldier were shooting and negotiating a series of obstacles encompassing a range of movements. Soldiers undertook the tests wearing different combinations of weapon and equipment with the instantiation of no weapon, no equipment being taken as the control instantiation.

The factors that will influence performance include test equipment, participant, weather, fatigue, learning, and participants' personal equipment. The only one of these factors that is of interest is the test equipment. Appropriate activities in which soldiers are required to be proficient where included in the test in order to reduce the impact of lack of prior training, learning and fatigue through the activity. Analysis, therefore, will need to utilise techniques such as blocking, controlling the variation in personal equipment and randomisation of conduct sequence to reduce or highlight the impact of the nuisance factors.

Selection of Measures and Supporting Data Capture

Considering the basic soldier skills of shooting activities, standard measurements consist of grouping and mean point of impact (MPI). The grouping is the spread in millimetres, of five consecutive shots. The MPI is the distance, in millimetres, of the centre of a group of five consecutive shots from the central aiming point. The MPI is expressed as two numbers reflecting the vectors up and right from the aiming point. Negative numbers indicate an MPI below or left of the aiming point. Collectively, the measures indicate consistency of performance against marksmanship principles with participants seeking to produce measures as close to zero as possible.

Performance in agility tests can be measured in the time taken to complete the activity (seconds) with each test being measured separately to demonstrate the impact of equipment on performance against specific actions.

In order to gather qualitative information about the use of the equipment and any impact on performance that does not manifest itself as a change in performance, a survey was conducted. Participants were asked to rate the impact of each instantiation on their performance using a Likert scale of 1 to 5 representing the range from strong improvement to strong hindrance of performance with no effect as the mid-point. They were also asked to provide clarifying comments and were interviewed to gain an understanding of the rationale for ratings, especially where strong variations were present. Follow-up interviews were conducted at the conclusion of the activity using methods highlighted in Minichiello et al (1990) and Strauss and Corbin (1990). Collection, collation and analysis of data through interviews and observations were refined from the lessons highlighted by Rees and Lush (2009) for military application.

Action

This section discusses the analysis of data that was undertaken during the case study. For the purposes of this paper, which focuses on the methods rather than results, data has been aggregated where necessary for simplicity. The intent of this paper is to illustrate the method rather than present the detailed analysis. As a basis for comparison, the analysis is presented in two parts; the first focuses on exploring the data while the second calculates the SICM Index.

Exploring the Data

In order to gain an understanding of the impact that each factor (the type of equipment) had on performance, the data was first analysed using conventional techniques. To reduce the variation introduced by the participants, variation against a baseline instantiation was chosen as the data to be explored. This was expressed as a percentage difference in performance between control equipment (the currently used systems) and performance under each combination of equipment. Statistical analysis of variance was also used to determine whether each factor has an impact on performance and whether there is any interaction between the factors.

Variation from Baseline

Figure 3, below, illustrates the graphical analysis of variation from baseline. This example considers the average variation for all participants by instantiation for six tests. The graph reveals that performance in the "Tunnel" is most affected by the different instantiations of the system suggesting further specialist analysis of the reason for the variation. It is also interesting to note that all instantiations in this case generated an increased response time.

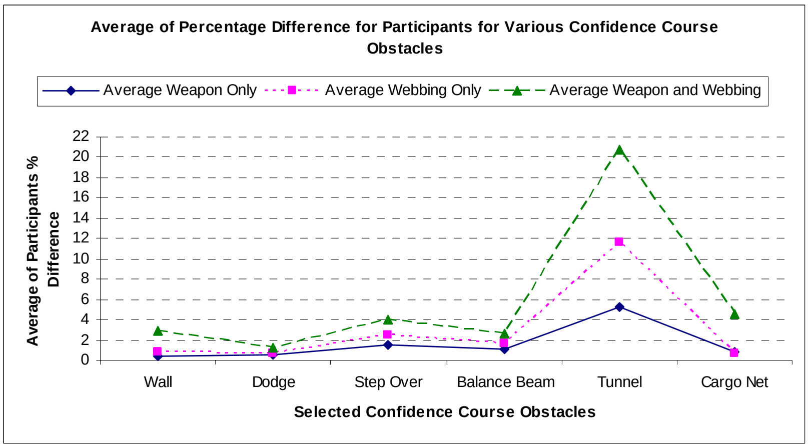

Figure 3 Percentage Difference to Baseline for Various Activities and Capability Options

The graph for variation against baseline in shooting activities shows negative and positive variations. The challenge for analysts is to identify which (if any) direction of change is desirable and which is undesirable and equating them appropriately for the decision. Figure 4, below, shows the percentage difference by participant for an activity using the same instantiation in a number of different shooting positions.

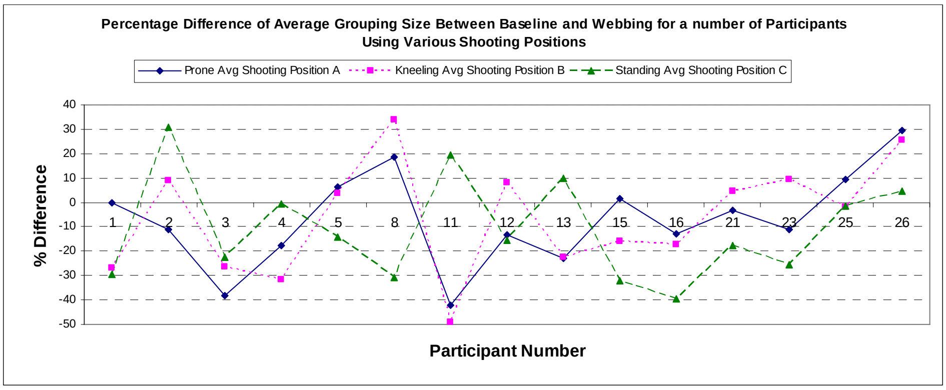

Figure 4 Percentage Difference by Participant for a Number of Shooting Positions

Analysis of Variance

The Analysis of Variance (ANOVA) is blocked to remove the impact of participant on the response measured. Table 1 shows an example for one of the tests using statistical analysis software. In this case, we can see that participant and sub–system have an effect on individual soldier performance. Further, the interaction between weapon and webbing do not have an impact on a 95% level of significance.

Table 1 Example Statistical Analysis of Variance - Tunnel Obstacle

	Degrees of Freedom	Sum of Sq	Mean Sq	F Value	Pr (>F)
Part	17	2355.66	138.57	5.4443	3.97E-07
Weapon	1	1363.05	1363.05	53.5535	6.575E-10
Webbing	1	3126.94	3126.94	122.8561	3.004E-16
Weapon and Webbing	1	87.4	89.14	3.4237	0.06911
Residuals	61	1552.58	25.42		

Graphically, a box plot (Figure 5) suggests that responses do vary under different combinations of equipment. It is interesting to note that the median response where only one factor was present appear close even though the distributions are different. This and the higher response when both factors are present suggest interaction needs to be explored further. Figure 6 shows the limited interaction between factors. Strong interaction would be revealed through the lines intersecting and having very different slopes. Strong negative interaction would suggest that a combination of equipment presents concerns that need to be investigated or avoided.

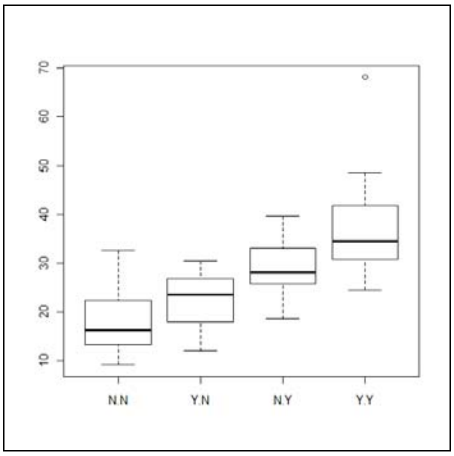

Figure 5 Box Plot of Performance by Combination of Factors

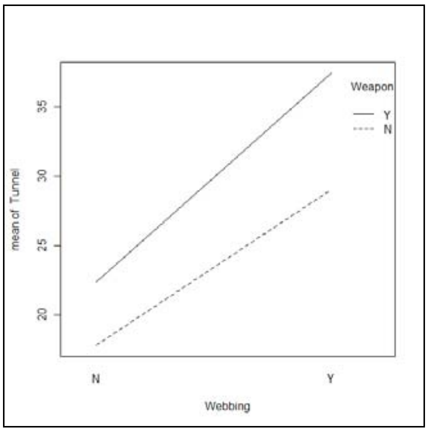

Figure 6 Example of the Interaction between Elements

Qualitative Analysis

Qualitative data was collected through a survey process using rating scales. The results are reviewed and analysed to provide the mechanism to include expert judgment as part of the empirical process. For example, should a number of respondents identify particular ergonomic concerns, these could be passed to human factors specialists for detailed examination.

Figure 7 shows a frequency plot of survey responses against the shooting positions used by the participants in each test. In this case, most participants reported no difficulty in performing the test in the control configuration. This is highlighted by the consistently high frequency of the rating of '3' assigned by participants; other ratings do not reveal such consistency.

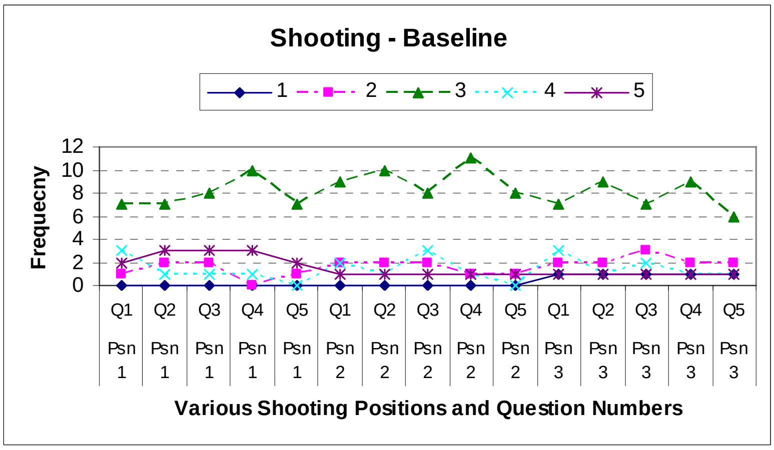

Figure 7 Example Frequency Plot for Survey Responses

Figure 8 is a frequency plot of survey responses for the same test as shown in Figure 7 but using a different instantiation. The graph shows a marked change which was explored through group interview and thematic analysis of survey comments.

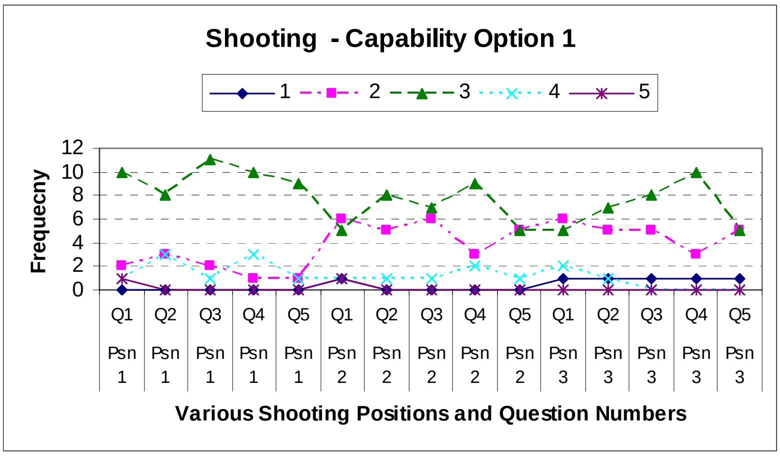

Figure 8 Example Frequency Plot for Capability Option 1

Qualitative analysis can be used to inform a number of aspects of the analysis. Identification of ergonomic and other HF issues for further exploration, issues not identified through performance variation (e.g. had to work harder to get same score), identify where individual preferences might be a factor and to identify system combinations. Variation in qualitative ratings may also be useful to inform the selection of the preferred combination of sub-systems to inform.

This exploration of the data suggests that the instantiation influences performance and, therefore, the selection of the solution needs to be considered as part of a system rather than sub-system performance alone. SICM provides such an approach.

Calculation of SICM Index

The SICM rating approach combines the qualitative and quantitative measures to present a comparative score for each instantiation. The aggregation method selected for the trial was a multi-criteria method using each test as a criteria and the average variation of performance against baseline as the rating for each instantiation. At this stage, weightings were not applied as no information was available as to whether the decision maker would apply a weighting system to these factors.

One matter of concern was the potential for the relative number of tests and questions to skew the results – the combined ratings of 15 qualitative questions could outweigh the combined result of five quantitative tests and the desired weightings of the decision-maker. To overcome this concern a scaling factor was applied to each calculated rating to generate a normalised score using equation (1).

$$r`_i = r_i \frac{n_{\max}}{n_i} \qquad (1)$$

where:

r` is the scaled rating for i^{th} attribute,
r is the % variation in performance from baseline for i^{th} attribute,
n_{max} is the maximum number of elements contributing to each rating, and
n is the number of elements contributing to the attribute being rated.

The desirable importance of each element can then be reflected through the assignment of a weighting applied through equation (2) to calculate a SICM score for each instantiation.

$$s_i = \sum_{j=1}^{m} \sum_{i=1}^{n} w_j r'_{ij} \qquad (2)$$

where:

s is the calculated score for i^{th} instantiation,

r`$_{ij}$ is the scaled rating for i^{th} attribute of the j^{th} test calculated in (1),

w is the weighting assigned to the j^{th} test,

n is the number of instantiations, and

m is the number of tests contributing to the score.

The result of these calculations was the generation of a vector representing the score for each instantiation as the basis of comparison. The calculated score provides a ready indicator to the decision-maker about the relative assessment of each combination of equipment as a system.

Summary

The approach provides mechanisms for comparing various capability options for decision makers. It allows interrogation of the problem space using a variety of analysis techniques. The novelty of the approach is in its ability to provide a single score representing various capability options, which accommodates both qualitative and quantitative data. This provides decisions makers with tangible results for comparison purposes.

Future Work

The approach explored the combination of techniques and is consistent with guidance relating to recognition of the "right" problem (Curtis *et al*, 2006). Some areas of analysis were identified but were excluded from the case study to allow testing of the general approach before further expansion of the technique. Two key areas of future research are under development – the determination of weightings for each attribute and the expansion of the model to incorporate the system of systems view of the decision being informed.

Conclusion

A method utilising qualitative and quantitative operations research techniques in combination with experimental design to develop multi-criteria approaches has been proposed to inform the selection of sub-systems for the soldier combat capabilities. Of primary interest in the method is its independence of military scenario, and the approach's ability to allow comparison of competing soldier close combat equipment options qualitatively and empirically.

The method is feasible and suitable for purpose, utilising a number of proven analytical tools and techniques for the gathering collating and analysing of data to support the selection of capability options. The iterative principle offered by Midgley (2000) provides for continuous improvement and incorporates efficiency in that the data only needs to be collect once and can be applied to various roles and environments if required. The technique's foundation in the skills of an individual soldier and the soldier's ability to perform on the battle field informed through the use of NATO provides an underlying guidance.

The method incorporates its own baseline providing a viable option for comparison for option selection. It combines qualitative and quantitative data which is analysed using a selection of tools providing a variety of perspectives for data interrogation and interpretation. Incorporation of weighting factors allows for the role specific nature of participants to be accommodated, this can also incorporate an environment as well, without needing to change the data collected. The case study demonstrated the viability of generating a single figure to represent the decision-maker's multiple perspectives of a number of system instantiations to inform a capability selection decision.

This method has questioned the underlying assumption about the aggregation function: looking for disproportionate effects, compound effects, unexpected relationships, and the impacts on overall performance, critical failure and weaknesses. To achieve this goal, comparison with a number of processes were explored and tested with a view to highlighting these effects.

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Multi-attributes Utility Theory and Statistical Analysis for Defence Future Vehicle Options

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Abstract

Land force future vehicles are being acquired to improve the fighting capability of the Australian Defence Force (ADF). The mission effectiveness of a combat vehicle is often measured by multiple attributes, so it is desirable to develop a Multi-Criteria Decision Analysis (MCDA) methodology to support upcoming decisions for operational capability of future vehicle options. To address this type of problem, DSTO has developed a ranking and selection procedure for making comparisons of options that have multiple performance measures. The procedure combines Multi-Attribute Utility Theory (MAUT), various weighting techniques and statistical analysis to rank the various options across different scenarios and environments. The purpose of this paper is to describe the application of our procedure to the results generated in an experimental war-game, with a realistic simulated environment, such that the options can be ranked and the best option selected for a specific task or scenario.

Key Words: Defence, Decision Modelling, Simulation

Introduction

Defence Science Technology Organisation (DSTO) has been investigating the characteristics of small combat teams and exploring future options for their composition, organisation and employment. Using a combination of war-gaming, closed-loop simulation and historical studies, these studies seek to understand the close combat capability factors that may govern the design of the future ADF. In particular, this work has focused on the analysis of future armoured vehicle options. Four experiments have already been conducted in support of this aim. These experiments investigated the impact of key vehicle characteristics such as lethality and survivability on the effectiveness of small combined arms teams engaged in close combat. This effectiveness was investigated in the context of different levels of physical environmental complexity, different levels of enemy lethality and different level of Exercise Force (EXFOR) aggressiveness.

The highest level metric for these studies was Mission Effectiveness, which is defined as the ability of the combat team to cause a desired result - that is successfully completing a military mission - while not causing an undesired result such as unintended harm to the operating environment. A range of contributing metrics were identified that informed mission effectiveness, including friendly casualties, civilian casualties, enemy casualties, and sensitive and non-sensitive infrastructure damage. Individually these metrics provided insights into specific characteristics of the vehicle equipped combat teams, however of greater analytical interest was the relative mission effectiveness of each of these combat teams in the various contexts explored.

Consequently the central focus of the quantitative analysis was to establish a multi-criteria measure of mission effectiveness that combined all of the individual metrics together with associated weightings for these metrics.

MCDA is divided into several schools of practice. Some of the main techniques are listed as below:

- Analytic Hierarchy Process (AHP) (Saaty, 1982)
- Simple Multi-Attribute Rating Technique Exploiting Ranks (SMARTER) (Edward *et al*, 1994)
- Data Envelope Analysis (DEA) (Charnes *et al*, 1978)
- ELimination Et Choix Traduisant la REalité (ELECTRE) (Roy, 1968)
- Preference Ranking Organisation METHod for Enrichment Evaluations (PROMENTHEE) (Brans *et al,* 1984)
- Evidential Reasoning Approach (ERA) (Yang *et al,* 1994)
- Technique for Order Preferences By Similarity to the Ideal Solution (TOPSIS) (Hwang *et al,* 1981)

AHP is hierarchical methods whereby decision problems are broken down into a hierarchy of sub-problems that can be analyzed independently. These methods are mainly applied to large-scale, multi-party problems and presented as interactive group activities. DEA generalise on linear programming to solve optimisation problems with multiple and possibly conflicting objectives. In essence, a decision is 'located' that is as 'close' to satisfying the objectives as possible. The objectives are actually coded as linear constraints defined by inequalities in the decision variables. A penalty function weighs the objectives relative to one another. ELECTRE and PROMETHEE are referred to as 'outranking' methods. Both make use of binary comparisons of alternatives. In general, they consist of two main parts: 1) constructing a series of outranking relations aimed at comparing each pair of actions; and 2) an exploitation procedure that elaborates on the recommendations obtained in the first phase. The nature of the recommendation depends on the problem being addressed. ERA assesses options based, in particular, on the theory of evidence (Schafer, 1976). A belief structure (or matrix) and evidential reasoning algorithms incorporate uncertainty and randomness aspects of decision making. Both qualitative and quantitative criteria are supported. TOPSIS (sometimes referred to as TOPSYS) is a popular *ideal point* method. In this method options are ranked according to their separation from an ideal point defined as the most desirable, weighted, hypothetical option. The separation is measured via a metric distance.

The above methods are fairly labour intensive, and the outcomes might not provide sufficient Justification for the extra effort given the usual uncertainty in the outcomes caused by the uncertainty of the used models. Therefore, in what follows, we limit our focus to methods that fall under the general classification of additive multi-attribute value or utility models. The Main reason for the limitation is that past studies in combat modeling by the authors have made extensive use of them, and in these studies certain issues have surfaced that is the subject of investigation later in this paper.

To date, two approaches have been explored in the defence problems domain. The first approach entailed an implementation of a committee consensus decision technique in which *n* objects (options) are ranked to reflect the consensus view of the committee across a range of weighted criteria (attribute) (Emond, 2006). The primary disadvantage of this method is that only ranking information from individual metrics are considered in establishing multi-criteria rankings. Actual mean or median values of the metrics are lost and this may result in large differences between two options in an individual metric being ignored in the final rankings.

The second approach employed Multi-Attribute Utility Theory (Keeney *et al*, 1993) to rank the options. MAUT preserves absolute differences in metrics between the options and may also provide a flexible decision support tool to aid decision makers by allowing a range of questions and contexts to be rapidly explored in the available data. This paper will illustrate the application of MAUT theory to the multi-criteria comparisons of the mission effectiveness of different vehicle options based on representative constructive simulation data.

Ranking and Selection Procedure

In this section we present a ranking and selection procedure for conducting comparisons of vehicle options that have multiple input parameters and multiple performance measures. This task is complicated by the large number of factors that impact the decisions and may have to be considered simultaneously. These factors can be represented by the performance measures to capture the effectiveness of the selected vehicle options. This section presents a ranking and selection procedure that combines Multi-Attributes Utility Theory (MAUT), Analytical Hierarchy Process (AHP) weight assessment method, constructive war-game simulation and statistical analysis for ranking and selecting the best vehicle option. The proposed procedure utilises computer war-game simulation to estimate the performance measures. It combines the advantages of both MAUT (Keeney *et al,* 1993) and AHP (Saaty, 1982). The advantages of MAUT lie in its ability to:

a) preserve the differences in quantitative measures between different options.
b) express the decision maker's degree of satisfaction (utility) for each attribute in the decision hierarchy as that attribute takes on values between the least and most preferred conditions.
c) construct utility functions in graphical form that capture the risk taking tendencies (aversion, prone, neutral) of the decision makers.
d) statistically analyse uncertainty output from probabilistic performance measures of constructive war-game simulations.

On the other hand, the advantages of the AHP lie on its capacity to:

a) establish the weights of attribute in a systematic and robust manner.
b) allow the decision maker to check the consistency of the rankings of the relative importance amongst the involved attributes.

Our proposed procedure is as below:

1. Define mission effectiveness goal & structure attributes and goal hierarchy
2. Conduct constructive war-game simulation experiments
3. Build up utility values from the simulation experiments
4. Define relative importance between the attributes by using AHP framework
5. Calculate expected utility values for the attribute and overall mission effectiveness goal
6. Conduct statistical analysis of the uncertainty utility values
7. Rank, analyse and select the best option

Constructive Simulations

A DSTO run human-in-the-loop war-game based experiment was conducted with military players using the Close Action Environment (CAEn)[2] war-game to examine future vehicles options using a method similar to (Coutts *et al*, 2008). These real time wargames allowed players to explore the strengths and weaknesses of the vehicle options and develop insights for more controlled follow on simulations.

The human-in-the-loop war-games were supplemented by a follow-up activity that involved closed-loop simulations in CAEn, purposefully developed to limit variations in the results caused by uncertainty and changes to, for example, the Exercise Force (EXFOR) Scheme of Manoeuvre[3] (SoM) and Opposition Force (OPFOR) actions. Military players from the war-gaming experiment assisted DSTO in constructing the schemes of manoeuvre for these simulations, based on the insights gained during the war-games. The results from this activity were used as an additional analytical source to the quantitative and qualitative analysis from the war-games.

<u>Design</u>

For this activity, a series of actions (for EXFOR and OPFOR) and triggers were scripted to represent the EXFOR actions from the war-games in a standardised form. The EXFOR players then devised a 'best case' SoM for the analysts to implement.

The EXFOR Order of Battle (ORBAT)[4] was essentially the same as in the original war-gaming experiment. The vehicle options were classed as heavy, medium or light[5]. Each option consisted of two Direct Fire Support (DFS) vehicles[6] and a total of six Armoured Personnel Carriers (APCs).

The variables used for comparison are detailed in the Table below:

Table 2. Constructive Simulation Scenario Variables

Variable	Possible Values
Terrain	Rural Village[7], Urban Environment
OPFOR	Insurgent, Conventional (Semi-Symmetrical)
Scheme of Manoeuvre	Aggressive, Cautious, Unspecified
Offensive Support (OS)[8]	Yes, No

[2] CAEn is an entity-level war-game simulation, written in C++, used to model operations up to company size. CAEn models such aspects of combat as manoeuvre, sensors and weapons effects using data intensive models (Shine et al, 2007) in a three-dimensional environment, typically designed to closely represent a real-life location. CAEn is used for combat modelling in the United Kingdom, Canada and Australia.

[3] A scheme of manoeuvre is the overall plan that a military force uses to undertake a mission and defeat an enemy. It includes details on the intent of the plan, the tasks assigned to different element of the force involved, timings, movement and tactics.

[4] An ORBAT is the list of units, personnel, equipment, etc in the scenario on each side represented..

[5] These categorisations are based on the armour and main weapon of each vehicle option.

[6] Tank or an armoured and heavily armed Infantry Fighting Vehicles (IFV) used in an intimate fire support role.

[7] A small settlement of approximately 100 low set buildings located in jungle with wide spacing between buildings relative to the urban environment..

[8] OS in this case is owned by EXFOR and includes155mm artillery and 81mm mortars.

The simulation cases constructed during the follow up activity are marked with an X in Table 3. Modifications were then made to these to get the additional cases for replication (marked with an 'o'). This means that the SoM implemented was exactly the same across the options. All cases were run both with and without OS.

Table 3. Constructive Simulation Cases run in replication

Terrain	OPFOR	SoM	Vehicle Option		
			Heavy	Medium	Light
Rural Village	Insurgent	Unspecified	o	X	o
Urban Environment	Insurgent	Cautious	o	X	o
		Aggressive	X	o	o
Urban Environment	Conventional	Cautious	o	X	o
		Aggressive	X	o	o

Performance Measures

The same Performance Measure metrics that were applied to the war-games were also applied to the constructive simulations. These metrics are:

- **EXFOR Casualties**. This metric is defined as a primary factor for performance calculations and is represented as a set of human EXFOR casualty figures for each closed-loop simulation run of the CAEn war-games. This measure only includes dismounted EXFOR infantry.
- **Civilian Casualties**. This metric, similar to EXFOR casualties, is a primary factor for performance calculations but represents civilian casualties.
- **OPFOR Casualties**. OPFOR casualties were considered a secondary factor for performance calculations and were represented as a set of human casualty figures for each closed loop simulation run of the CAEn war-games. This measure only includes dismounted OPFOR combatants.
- **EXFOR Vehicle Casualties.** Vehicle casualties can either be partial damage or catastrophic kills of an EXFOR DFS vehicle or APC. This metric is a direct indicator of the vulnerability of the vehicles in any particular option.
- **Damage to Sensitive Infrastructure**. A low level of damage to sensitive Infrastructure was considered as important as reducing EXFOR and civilian casualties. This metric is defined as a primary factor for performance calculations.
- **Damage to Non-Sensitive Infrastructure**. This metric was similar to the Damage to Sensitive Infrastructure metric, but calculated damage to all infrastructures in the area of operations, rather than just sensitive infrastructure. This was considered a secondary factor for performance calculations, of equal weight with OPFOR casualties.

Multi-Attribute Utility Theory

Utility Theory was introduced by Neumann and Morgenstern (Neumann *et al*, 1947) and this theory relies on the utility axioms that involve risk and uncertainty. MAUT was based on Utility Theory and was developed by Keeney and Raiffa (Keeney *et al*, 1993). One common feature in the MAUT based methods is that they estimate and fit utility functions and probability to the performance measures. After generating these utility functions for all performance measures involved, the decision makers can explore any number of alternatives (options) presented to them to make the decision. The MAUT procedure applied in this paper will follow the following steps:

- Structure the problem by tree-like goal hierarchy
- Defining the option and evaluating performance measures for each option
- Constructing Single-Attribute Utility Function (SUF)
- Assessing weights between different attributes
- Constructing Multi-attribute Utility Function (MUF)
- Computing expected utility value and uncertainty utility values
- Ranking and exploring options based on the computed utility values

Mission Effectiveness Goal Hierarchy

The attributes that influence mission effectiveness should be identified in order to construct the decision hierarchy that best suits the mission effectiveness ranking strategy. The goals hierarchy for a MAUT analysis is a tree-like structuring of the goals, measures, and measure categories in the analysis. In a goals hierarchy the highest level "Overall" goal is at the top of the hierarchy. The Overall goal's members are below it. Similarly, the members of each goal are below the goal they belong to. The goal hierarchy is showed in Figure 9.

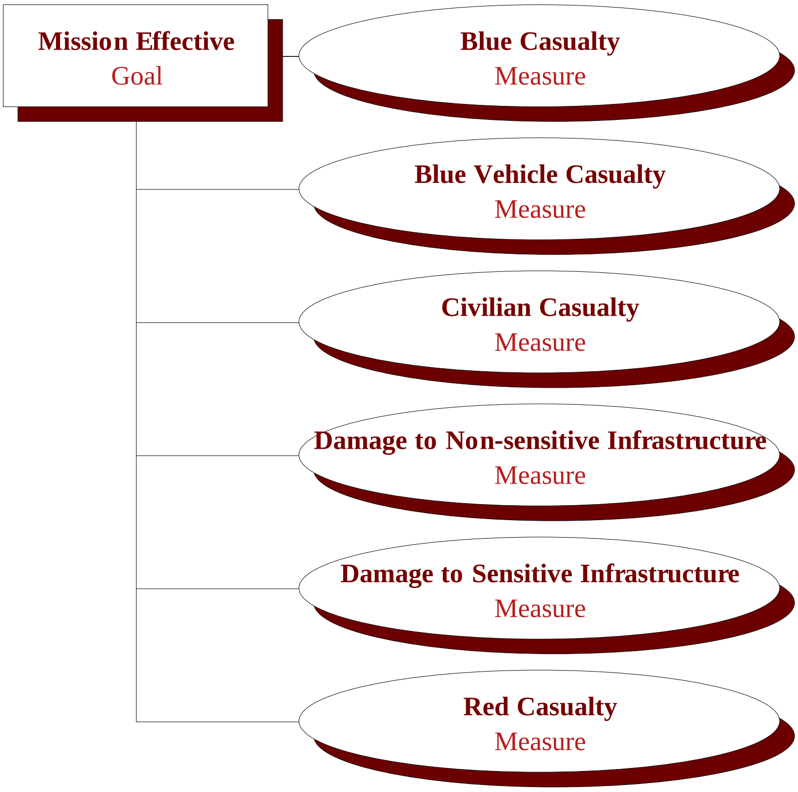

Figure 9: Goal Hierarchy for mission effectiveness

Single-Attribute Utility Functions (SUF)

Single-attribute utility functions are used to quantify the preference of the decision maker by assigning a numerical index to various degrees of satisfaction as the attribute under consideration takes values between the most and least desirable limits. These limits are defined for each attribute using any preferred units. It has been recommended that utility functions be monotonic (Keeney *et al*, 1993). The most desirable scenario corresponds to the highest utility, $u(x_i) = 1$, whereas the least desirable scenario corresponds to the lowest utility, $u(x_i) = 0, i=1,\ldots,n$.

The decision maker's attitude towards risk has been accounted for using a set of utility functions. In the risk averse attitude, the values of certainty equivalence, $\hat{x}$, (which corresponds to 0.5 utility) is less than the average value of the attribute's limits (x_L and x_U). In this case, the condition $\hat{x} < (x_L + x_U)/2$ must be satisfied. The utility function that represents this attitude can be expressed either by a piecewise linear function or an exponential function. The utility function that represents the risk prone attitude can, similarly, be expressed either by a piecewise linear function or a logarithmic function. In this case, the condition $\hat{x} > (x_L + x_U)/2$ must be satisfied. In the risk neutral attitude, the condition $\hat{x} = (x_L + x_U)/2$ must be satisfied and the utility function can be expressed by a linear function.

Multi-Attribute Utility Functions (MUF)

There are typically two formulas for MUFs. The additive formula is used when there are no interactions between the attributes. The additive formula is a simple weighted average of the utilities of the attributes:

$$U(X) = \sum_{i=1}^{n} k_i u_i(X) \tag{1}$$

Where $U(X)$ is the overall utility of alternative X, $u_i(X) =$ the utility of X for the ith attribute, and $k_i =$ the scaling constant small *k* for the ith attribute. The additive formula requires that $\sum_{i=1}^{n} k_i = 1$ and the scaling constants k_i can be interpreted as the attributes' weights.

The second MUF formula is the multiplicative formula. It is used when there are interactions between the attributes. The multiplicative MUF formula requires an additional scaling constant *K*. The value of *K* indicates the degree of interactions between the attributes. The multiplicative MUF formula can be written as follows:

$$U(X) = \left(\prod_{i=1}^{n}[1 + Kk_i u_i(X)] - 1\right)/K \tag{2}$$

Where $U(X)$ is the utility of alternative X, $u_i(X)$ is the utility of X for the ith attribute, *K* is a constant that is associated with *g* and k_i is the scaling constant for the ith attribute. *K* can be interpreted as an indication of the degree of interaction between the members below a goal hierarchy (see Figure 1). The level of K can result in several types of interaction between evaluation measures as below:

Value of K	Sum of k_i	Type of interaction
-1 < K < 0	> 1	**Constructive:** high utility in one measure means high utility overall
K = 0	= 1	**Neutral:** use additive MUF formula
K < 0	< 1	**Destructive:** low utility in one measure means low utility overall

The extreme case of destructive interaction is when *K* approaches infinity. Then the MUF formula becomes a pure product of the member utilities. Details about multiplicative MUF is in.

For simplicity, we assume the attributes are independent and therefore use the additive MUF formula with risk neutral (linear function) SUF in this paper. However, we will explore the issues of interaction in future work.

Weight Assessment Methods

The weights in additive MUF formula define the relative importance of the attributes and performance measures in the analysis. The following weight assessment methods are widely used in the current literature:

- **Direct Entry** directly enter subjective weights
- **Trade-off** (Schoemaker *et al*, 1982) defines the weights for a goal's active member by defining pairwise tradeoffs between the members.
- **SMART method** (Edward *et al*, 1994) defines relative importance using "swing weights".
- **SMARTER method** (Edward *et al*, 1994 and Jia *et al*, 1998) defines weights based on an ordering of relative importance
- **Pairwise Weight Ratios Method** (Belton *et al*, 2002) like the trade-off method, except that instead of defining a complete trade-off, you simply enter the ratio between the two members' weights.
- **AHP Weight Assessment** (Saaty, 1982) is an extension of the pairwise weight ratios method. Instead of entering ratios for selected pairs of active members, the ratios for ALL pairs are entered.

In this paper, the AHP weight assessment method is used to generate the relative weights associated with the attributes considered in the goal hierarchy. The AHP is used because the ratios of all possible pairs of attributes are likely to be inconsistent and the AHP can compute the best fit set of weights and the consistency ratio based on the entered weight ratios. The procedure is based on pairwise comparison among the attributes using a numerical scale from 1 to 9, where 1 indicates equal importance of the two attributes under consideration and 9 indicates absolute importance of one over the other. Upon completion of the pairwise comparisons and formation of the matrix of comparisons, the eigenvalues and eigenvectors are then obtained. The eigenvector represents directly the relative weights of the attributes (i.e. their relative importance) and the eigenvalue represents the consistency of the decision maker in assigning the relative importance of the attributes during the process of pairwise comparisons. The developers of the AHP method recommend that the consistency ratio (C.R.) should be below 0.1.

Mission Effectiveness Utility Values with Uncertainty Variables and Monte Carlo Simulation

Assuming mutually independent attributes, a simple additive utility model is used. As a result, the expected mission effectiveness utility is the weighted sum of expected utilities of all attributes in the goal hierarchy. However, performance measures for the vehicle options generated from constructive war-game simulation are random variables with probability distributions. It can be very difficult[9] to combine different probability distributions and this is particularly true with complex SUFs and MUFs. Monte Carlo simulation[10] (Rubinstein *et al*, 2007) avoids this problem by using a random number generator to produce random samples from the probabilistic levels from each performance measure to provide an estimate of the combined distribution. Each set of performance measure samples is used to compute the utility of one possible outcome, referred to as a trial. Many trials are conducted and the results can be used as an estimate of the cumulative probability distribution of the desired utility.

Numerical Results & Discussion

In this section, we illustrate our methodology with an example. Although the data used in the example are the results of the constructive simulation which are based on realistic military scenarios and planning. The results shown in this paper may be sensitive to the scenario used and are dependent on the weighting scheme. However, they are used here to demonstrate our methodology. The performance measures are EXFOR casualties, OPFOR casualties, Civilian casualties, EXFOR vehicle casualties, Damage to Non-Sensitive Infrastructure and Damage to Sensitive Infrastructure. The SUF was a linear function and MUF was constructed from a weighted sum of six SUFs. The weight assessment matrix was established based on the author's subjective judgement to illustrate the method and the weights were calculated by AHP weight assessment method. The assessment matrix as detailed below:

Table 4: The AHP weights assessment matrix

	EXFOR	Vehicle	Civilian	Damaged Non-Sensitive	Damaged Sensitive	OPFOR
EXFOR	1	1	1	3	1	3
Vehicle	1	1	1	3	1	1
Civilian	1	1	1	3	1	1
Non-Sensitive	1/3	1/3	1/3	1	1	1
Sensitive	1	1	1	1	1	1
OPFOR	1/3	1	1	1	1	1

The weights for the six performance measures EXFOR Casualties, OPFOR Casualties, EXFOR Vehicle Casualties, Civilian Casualties, and Damage to Non-Sensitive Infrastructure and Damage to Sensitive Infrastructure are 0.23, 0.19, 0.19, 0.1, 0.16 and 0.13 respectively. The consistency

[9] Closed form of convolution of distributions are very difficult to obtain (Beaulieu *et al*, 2004)

[10] Monte Carlo Simulation is a method for estimating the uncertainty of a variable that is a complex function of one or more probability distributions.

ratio is 0.044 that is within the recommended value of 0.1. If the consistency ratio is higher than 0.1, the weight assessment matrix should be revised.

The performance measures are generated 200 times for each option and input variables. These values are then fitted into the form of probability distributions and the uncertainty utilities are estimated by Monte Carlo simulation with 100 trials. The results of the average of the means of utilities with various simulation inputs are shown in Figure 2. We observe that, when aggregated over the range of cases, the:

- light option is the best in the cases with or without offensive support operations
- heavy and light options are the best for aggressive and cautious schemes of manoeuvre, respectively.
- heavy option performs slightly better than the light option in urban terrain but that the light option is clearly better in rural terrain.
- light option is the best for both insurgent and conventional OPFOR.

These results are arbitrary and based on an artificial selection of weightings designed to illustrate the methodology. If a formal study was to be conducted using this method and real data, extensive consultation with subject matter advisors would be required in order to establish a valid weighting matrix.

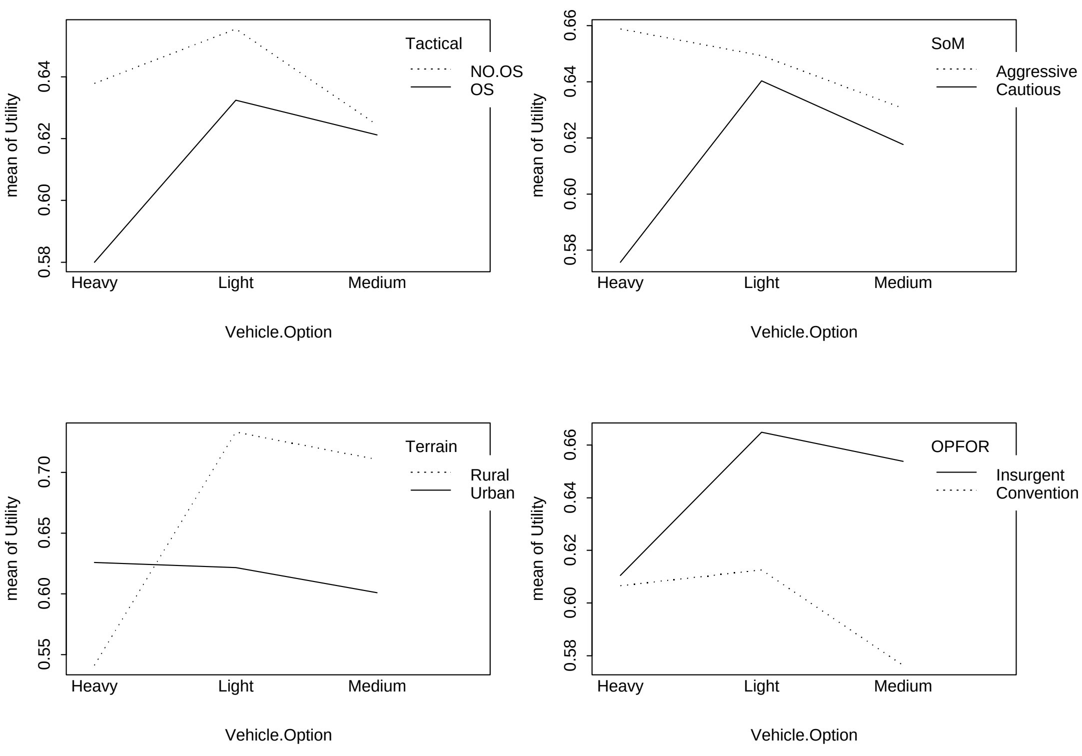

Figure 10: Vehicle Option vs. Expected Utility with various simulation inputs

The uncertainty results for cases with urban terrain and a cautious SoM are shown in Table 8. These tables are not a complete set for all combinations of variables but are included to illustrate uncertainty results from this example. We observe that the standard deviations are small, the ranking of options based on uncertainty utility values (mean, median, minimum, 5th Percentile, 95th percentile and maximum) are consistent and therefore we have sufficient confidence to accept the ranking results. The ranking results here indicated that light option is the best for all different variable inputs (Terrains, SoM and OPFOR) and all uncertainty measures (mean, median, percentiles etc).

Table 5: Utility uncertainty summary for Mission Effective Goal with Offensive Support and Terrain = Urban, SoM = Cautious, OPFOR = Insurgent.

Vehicle.Option	Mean	Std. Dev.	Median	Min.	5th Percentile	95th Percentile	Max.
Heavy	0.61	0.053	0.615	0.44	0.514	0.679	0.758
Medium	0.6	0.048	0.605	0.444	0.512	0.663	0.735
Light	0.507	0.057	0.513	0.323	0.403	0.582	0.667

Table 6: Utility uncertainty summary for Mission Effective Goal without Offensive Support and Terrain = Urban, SoM = Cautious, OPFOR = Insurgent.

Vehicle.Option	Mean	Std. Dev.	Median	Min.	5th Percentile	95th Percentile	Max.
Heavy	0.67	0.034	0.673	0.56	0.608	0.714	0.765
Medium	0.615	0.038	0.619	0.492	0.545	0.665	0.722
Light	0.694	0.036	0.698	0.579	0.629	0.741	0.794

Table 7: Utility uncertainty summary for Mission Effective Goal with Offensive Support and Terrain = Urban, SoM = Cautious, OPFOR = Conventional.

Vehicle.Option	Mean	Std. Dev.	Median	Min.	5th Percentile	95th Percentile	Max.
Heavy	0.541	0.049	0.546	0.381	0.45	0.606	0.679
Medium	0.55	0.06	0.556	0.355	0.44	0.629	0.719
Light	0.582	0.058	0.588	0.396	0.476	0.657	0.743

Table 8: Utility uncertainty summary for Mission Effective Goal without Offensive Support and Terrain = Urban, SoM = Cautious, OPFOR = Conventional.

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Conclusion

In this paper, we have developed a ranking and selection procedure applied to multiple future combat vehicle options that are evaluated on multiple performance measures. The procedure relies on the ideas and techniques found in MAUT. Our example demonstrates that it can be applied to compare the combat value (mission effectiveness) of different vehicle options, via constructive simulation war-games, as part of a broader selection process. We claim that this method can also be extended to include broader vehicle selection criteria such as reliability, maintenance costs etc. The use of additive MAUT essentially provides a formal mechanism to rank and to explore mission effectiveness utility with probabilistic performance measures. However, the additive model requires the assumption of mutual attributes independence and this is not realistic. For example, EXFOR and OPFOR casualties are not quite independent. In our future work, we will explore the multiplicative model to analyse the trade-offs between options and the interactions between dependent attributes.

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[1] Higgins, J.C. and Finn, R. Managerial Attitudes Towards Computer Models for Planning and Control. Long Range Planning, Vol. 4, pp 107-112. (Dec. 1976).

[2] Simon, H.A. The New Science of Management Decision. Rev. Ed. Prentice-Hall, N.J. (1977).

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