HOLONIC CONTROL SYSTEM: A PROPOSED SOLUTION FOR MANAGING DYNAMIC EVENTS IN A DISTRIBUTED MANUFACTURING ENVIRONMENT

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ABSTRACT

Due to globalization, manufacturing of products is no longer a local activity done by a single company but rather a distributed venture as more firms are realizing the need to improve their flexibility and agility. The paradigm of e-manufacturing is gaining popularity among researchers and manufacturers who aim to improve their market share and shop floor visibility by belonging to larger collaborative networks. However, real-time events which lead to operational disturbances in a plant remain a challenge most manufacturers face since they result in deviation from initially prepared process plans and schedules, rendering them invalid before they can be launched on to the shop floor for implementation. The paper presents a Holonic Control System (HCS) as a proposed solution to managing this pandemic. The research focused on manufacturing firms in the Western Cape of South Africa which belong to the tooling industry. Cited in this paper are holonic architecture together with the success factors and barriers to implementing holonic control systems in South Africa. Results of the proposed system were generated by a simulation model and revealed that delivery time and resource utilization were improved by adopting the system.

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1 INTRODUCTION

Customers make the business world go round. It is common knowledge in the business world today that customers are the life blood of organisations. Lack of customers or depletion of customer base has seen businesses fold up at an alarmingly fast rate. The question that remains for sustained survival in the cutthroat business environment is; what needs to be in place to ensure that customers stay? The answer that has been heralded of late from a manufacturing perspective is the design and installation of e-manufacturing systems. Nyanga et al. [1] proposed the installation of an e-manufacturing system as a viable solution for facilitating manufacturers in South Africa to form collborative networks. These systems are expected to facilitate enterprise integration, cooperation among organizations and distributed manufacturing via the internet thus ensuring customer needs are met with improved shop-floor visibility.

E-manufacturing systems can also aid in generating optimal process plans and schedules for manufacturing goods in response to customer demand through the use of Multi Agent Systems (MAS) [2]. However, during tool room operations, events rarely go as expected as scheduled orders may get cancelled while new jobs are inserted. In addition, certain machinery for production may become unavailable due to breakdowns or scheduled maintenance, while newly purchased resources can be introduced. In some cases, scheduled tasks may take longer than anticipated. Other uncertainties like operator absence, unavailability of tools and depletion of raw materials are possibilities. These unforeseen dynamic events on the shop-floor can render an optimal process plan and schedule generated earlier after considerable effort unacceptable. If this happens, a new schedule must be generated to restore system performance and maintain achievement of business goals competitvely. A possible solution to this challenge is the design and installation of Holonic Control Systems (HCS). According to Wyns [3], these applications promise benefits that a holonic organizations provide to living organisms and societies; stability in the face of disturbances, adaptability and flexibility in the face of change, and the efficient use of available resources.

The paper presents a proposed Holonic Control System for the South African Tool, Die and Mould-making (TDM) sector in the Western Cape Province which enables real-time process planning and dynamic rescheduling in a distributed manufacturing environment. The organisation of the paper is as follows: firstly the concept of holonic manufacturing is discussed, then the proposed Holonic Control System architecure is presented together with the success factors and barriers for its implementation and lastly there is a presentation of the system's simulation results to support system efficacy.

2 THE HOLONIC CONCEPT

In a quest to describe how social and biological systems evolve, Koestler [5] initiated the concept of a Holon. In his study, he observed that living and organizational systems are made up of entities where almost every discernible element can be simultaneously perceived as a whole (an essential autonomous body) and a part (a cooperative integrated section of a larger more capable body). These systems were observed to adapt to new environments by evolving through self-reorganization and growing by extending themselves in an effort to satisfy internal and external changing conditions. This evolution resulted in stable, self-resilient and more capable systems than the ones that initially existed.

With these findings, Koestler [5] proposed the term "holon" which is a combination of Greek prefix "holos" meaning whole and Greek suffix "on" meaning part to describe such autonomous and cooperative elements of a system. Decades later, a Japanese scientist, Suda [6], indicated that such properties would be very essential for a manufacturing operation or system subject to increasing demands and rapidly changing conditions. He redefined a Holon in the manufacturing context as a building block of a manufacturing system for designing and operating elements [7].

2.1 Holonic Manufacturing System

Based on the findings of Suda's preliminary work, researchers have been motivated to translate the holonic concept to a manufacturing set-up. In 1994, a Holonic Manufacturing System Consortium (under the Intelligent Manufacturing Systems project) was formulated which constituted of research institutes, universities and industrial partners from Europe, America and parts of Asia. The purpose of this consortium was to conduct research by creating test-beds, prototypes and applications which employ holonic systems properties in a manufacturing set-up so as to see the benefits before industrial adoption. During these studies, a set of definitions were proposed for the holonic concept in a manufacturing perspective [8]. These key terms are defined in Table 1.

Table 1: Holonic Manufacturing Systems terms

Term	**Definition**
Holon	*An autonomous and cooperative building block of a manufacturing system for transforming, transporting, storing and/or validating information and physical objects. The Holon consists of an information processing part often a physical processing part (Figure 1).*
Autonomy	*The capability of an entity to create and control the execution of its own plans and strategies.*
Cooperation	*A process whereby a set of entities develop mutually acceptable plans and executes those plans.*
Holarchy	*A system of holons that can cooperate to achieve a goal or objective. The holarchy defines the basic rules of the cooperation of the holons and thereby limits their autonomy.*
Holonic Manufacturing System	*A holarchy that integrates the entire range of manufacturing activities from order booking through design, production and marketing to realize the agile manufacturing enterprise.*

2.2 Holon structure and properties

Wyns and Langer [9] proposed a generic structure of a Holon as illustrated in Figure 1. A Holon can interact with its environment which may consist of human operators, machinery and other holons via specific communication protocols. Humans communicate with the Holon via the human interface while other holons communicate with the Holon via the inter-holon interface. Physical components and machinery can be controlled via the Holon's physical part. Hence, Holons are computerized entities capable of doing specific tasks within a manufacturing environment on behalf of their users.

When holons cooperate with each other to achieve a goal, they are said to form a holarchy. Holarchies can be created or dissolved dynamically depending on the current needs of a manufacturing process. This key feature makes Holonic Manufacturing Systems possess the following essential properties:

- Self-organization: Holons enable manufacturing units to collect and arrange themselves in order to achieve a production goal.
- Reconfigurability: a manufacturing unit's function can be altered in a timely and cost effective manner in response to sudden changes or new demands.

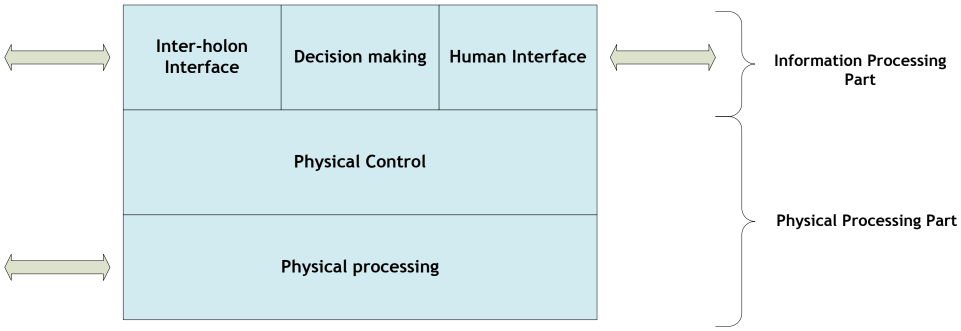

Figure 1: General Structure of a Holon [9]

2.3 Reference architecture

The first Holonic Manufacturing System architecture was proposed by Wyns [3], [4], during his studies at Katholieke University of Leuven. The architecture, referred to as PROSA (Product Resource Order Staff Architecture) consists of three basic Holons and an optional staff Holon as key components defining a manufacturing system. The identified basic Holons were defined as:

- Product Holon (PH): carries all the information about the products in a manufacturing system. The data includes bill of materials, process plans, levels of quality and product lifetime.
- Resource Holon (RH): represents the value addition part of the system which identifies the machinery, equipment, operators and transporters in a manufacturing system.
- Order Holon (OH): represent the customer requirements which are translated to system tasks.

These basic holons exchange production system information in a timely manner as shown by the architecture illustrated in Figure 2. Staff Holons (SH) representing human functions in a system can be added to supply expert knowledge to other Holons. These Staff Holons represent tasks that a competent person can do in a manufacturing facility.

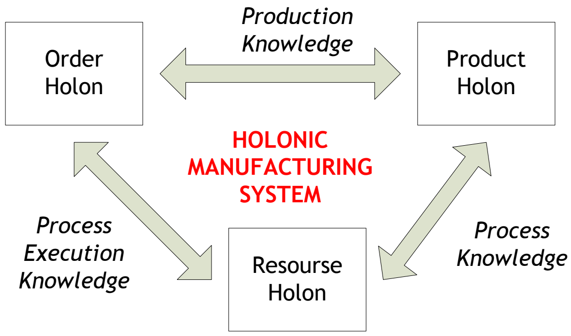

Figure 2: HMS Reference Architecture [4]

This architecture attracted many researchers and scholars who used it to build holonic control systems for different manufacturing settings.

2.4 Holonic Control System prototypes and applications

Extensive work and developed prototypes addressing control in planning and scheduling of manufacturing systems using the holonic manufacturing system approach exist. Chirn and McFarlane [10] built a holonic control system for a robotic assembly cell so as to enable it to cope with increased requirements of production change. In an effort to improve material handling operations, Babiceanu [11] developed a holonic based control system for generating a feasible schedule for the material handling resources given real-time constraints. A holonic control system was also developed by Roulet-Dubonnet and Ystgaard [12] for a flexible reconfigurable assembly cell. The study was conducted to solve the problem of frequent changes in the product spectrum and size. In other studies, holonic scheduling was successfully implemented in a die casting flow-line manufacturing system by Bal and Hashemipour [13]. Results of all these studies portrayed that uptime efficiency and the production rate of the manufacturing systems were significantly improved by the approach. It was observed in the studies done that the Holons utilized in the systems helped to improve the reaction of the systems to changing market or business requirements, the production of products more efficiently and better utilization of available resources.

2.5 Holonic Control System for South Africa TDM sector

Most firms in the South African tooling industry have been failing to compete with companies in Asia and Europe who have adapted to a modern manufacturing environment and embraced 21st century manufacturing principles and technologies that allow them to be competitive in a global arena. An Engineering Artisan Article [14] revealed that one of the key success factors for firms doing well in the tooling industry is product-time-to-market. However, according to Geyer and Bruwer [15], a majority of South African manufacturers in the tooling industry are uncompetitive with lead times and due date reliability resulting in them losing market share to firms in more developed nations who are adopting industry best practices. The main reason for this challenge is that operational disturbances resulting from late delivery of raw materials, machine failure, rush orders and market changes affect the smooth running of operations. The currently adopted planning and scheduling systems in South African tool, die and mould making organizations fail to handle such dynamic changes. This leads to compromising of system availability which results in late order deliveries.

The problem creates a need for the adoption of new computerized planning and scheduling systems which facilitate system reconfigurability, self-organization and real-time response to changes in the business environment, a gap holonic control systems can fill.

3 METHODS AND MATERIALS

Giret and Botti [16]'s proposed methodology for analysis and design of a Holonic Manufacturing System was used in the study. It involves establishment of the system requirements and design of the Holonic Control System architecture. The flow diagram for the procedure is presented in Figure 3.

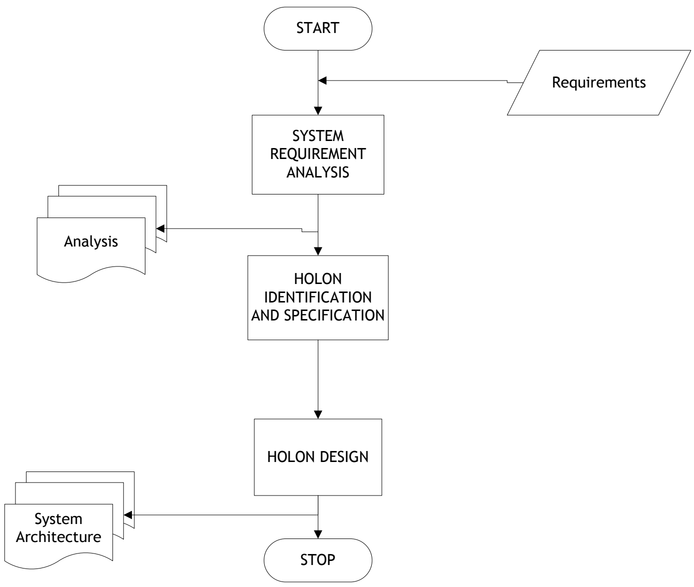

Figure 3: HMS Analysis and design stages [14]

To establish the requirements for the system, in-person, structured interviews were conducted. This method was specifically chosen because according to Sullivan et al. [17], interviews allow researchers to obtain large amounts of data and perform in-depth probing. The method helped to get information for model or system building. The purpose of the interviews was to establish frequently experienced operational disturbances in the tool and die industry in South Africa. The tooling industry in South Africa serves the Packaging, Food, Automotive, Mining and Plastic Forming industries. The Delphi or Expert Opinion methodology was used to select the appropriate respondents who were operations management personnel in the South African tooling sector. The selection was also based on potential users of the system. For the different industrial sectors, a tool room was selected to represent each sector making a selected group of five firms. Similar close-ended questions were used so as to compare the responses. To encourage participation of respondents, the purpose of the study was explained while confidentiality of findings was assured.

The findings from the interview would help in the systems analysis and design phase where a blue print of the system functionality would be presented in the form of a use case model. The analysis phase results in identification of the Holarchies, the Holons in the system and eventually the Holonic Control System architecture.

4 ANALYSIS AND DESIGN OF HOLONIC CONTROL SYSTEM

According to findings of the interviews, the most significant operational disturbances experienced by firms in the TDM sector were:

- Machine breakdown
- Raw materials and spare part stock outs
- Work build-up
- Equipment damage

The use of inappropriate maintenance procedures, late delivery by suppliers, supplier transportation problems, rush orders and supplier production problems were attributed to be the main root causes for the experienced operational disturbances. These findings were used to map the holonic control system requirements.

4.1 Holonic Control System requirements

Figure 4 summarizes the relationship existing between the dynamic events and operational disturbances experienced in the South African tooling industry. This helped establish the corresponding engineering functional requirements the holonic control system should address. To address the identified operational disturbances and their root causes, the Holonic Control System should facilitate Capacity Management of resources, Inventory Management of raw materials and spare parts and Maintenance Management of system resources.

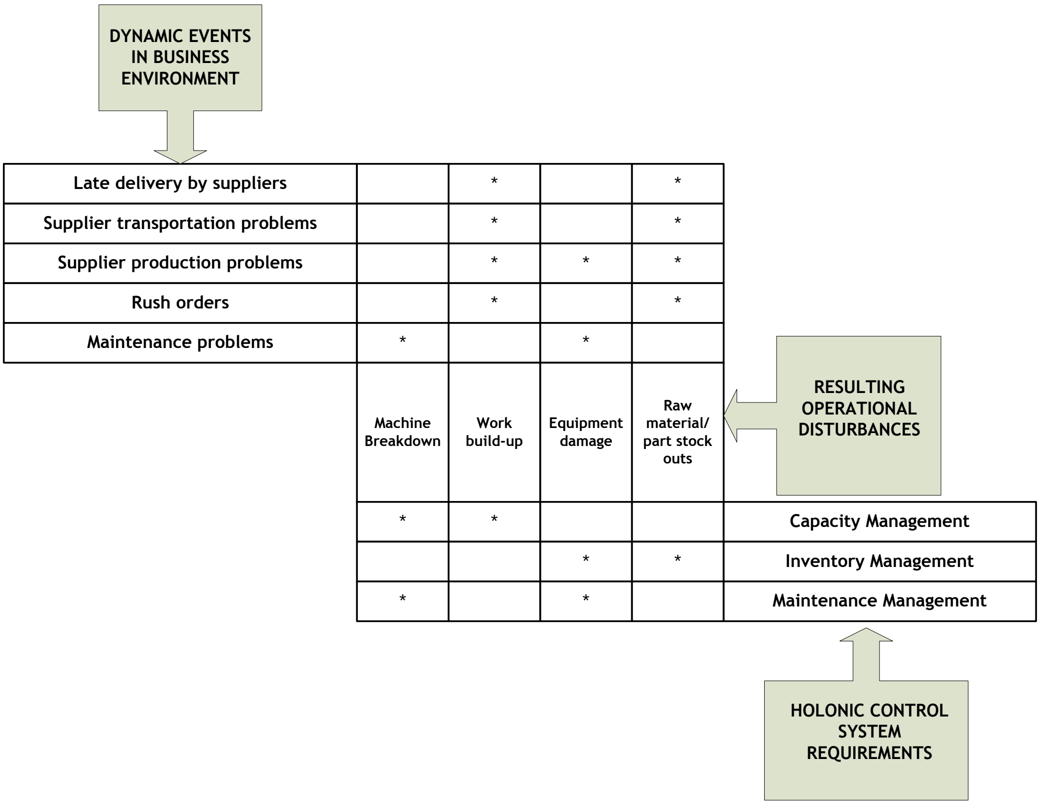

Figure 4: Holonic Control System Requirements

4.2 Use Case Model

Based on the derived Holonic Control System requirements, a use case model was developed to outline the different functions of the system. According to Fletcher et al. [18], use case models help in defining the system goals and domain of operation. A final use case model was developed as illustrated in Figure 5.

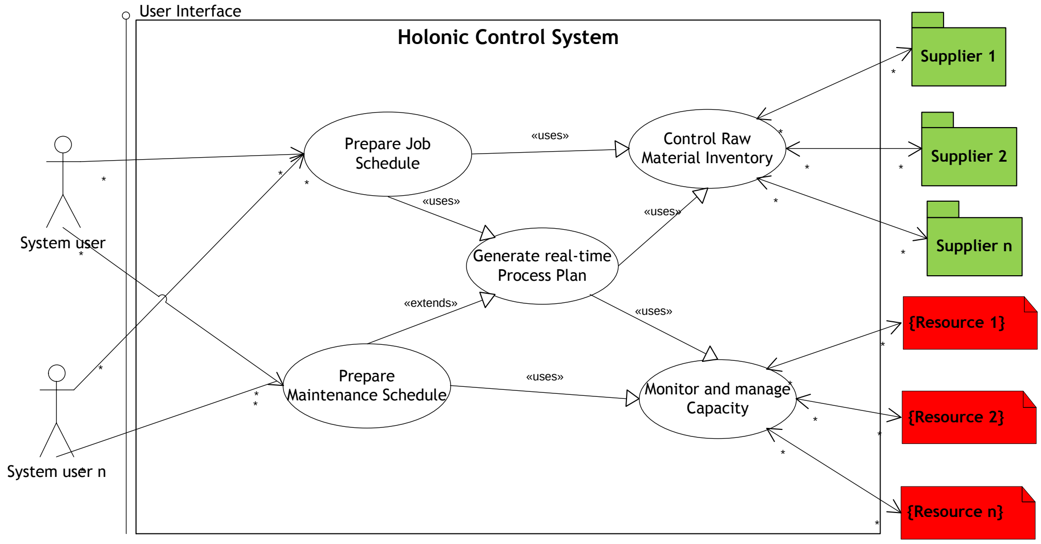

Figure 5: Holonic Control System Use Case Model

The main goals of the system as shown in the use case model are to prepare a schedule for orders and maintenance of machinery in the distributed manufacturing environment. The job scheduling function depends on real-time process planning which uses the raw material inventory control and capacity control functions. System users, who can be operations management personnel, interact with the system by obtaining a feasible job schedule and maintenance plan. The inventory control function is linked to the different suppliers while the capacity monitoring and management function is linked to all the resources (machinery) used in the entire distributed manufacturing system.

4.3 System Holarchies and Holons

The system functions derived from the use case model were used to define the system Holarchies. Each Holarchy contains a set of Holons responsible for accomplishing specific tasks which ultimately solve the sub-problem addressed by the Holarchy. The main Holarchies identified for the proposed Holonic Control System were:

- Inventory Control Holarchy
- Resource Planning Holarchy
- Process Planning Holarchy
- Job Scheduling Holarchy
- Maintenance Management Holarchy

Table 2 summarizes the Holons identified in each Holarchy.

Table 2: Identified Holarchies and Holons

System requirement	Identified Holarchies	Identified Holons
Inventory Management	Inventory Control	• Supplier Holon • Purchasing Holon • Inventory Level Holon • Buffer Holon
Capacity Management	Resource Planning	• Resource Holon • Supervisor Holon • Availability Holon
	Process Planning	• Bill Of Materials Holon • Resource Holon • Routing Holon • Availability Holon
	Job Scheduling	• Order Holon • Routing Holon • Scheduling Holon
Maintenance Management	Maintenance Management	• Resource Holon • Availability Holon • Maintenance Planner Holon • Inventory Level Holon

A Holon can belong to more than one Holarchies. The Inventory Level Holon, Availability Holon and Resource Holon each belong to two or more Holarchies.

4.4 Holonic Control System Architecture

An interaction model was utilized to present the system architecture for the proposed Holonic Control System. The notation for the symbols used in the system architecture is shown in Figure 6.The architecture is illustrated in Figure 7 below showing how the different Holarchies communicate and coordinate their functions in response to different operational disturbances occurring in the business environment.

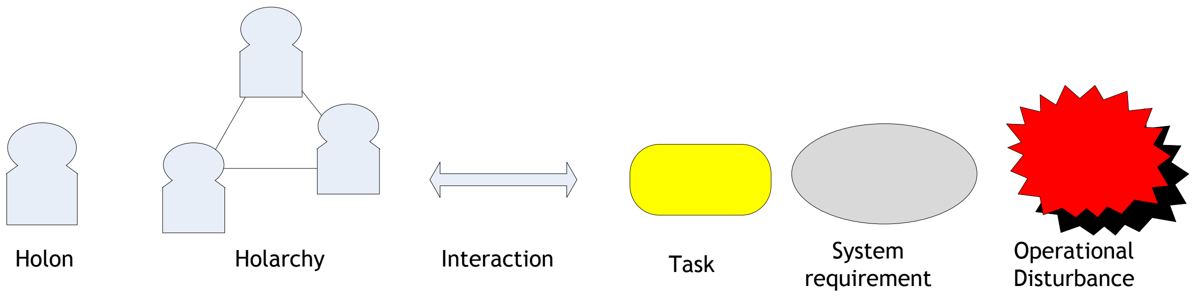

Figure 6: Notation

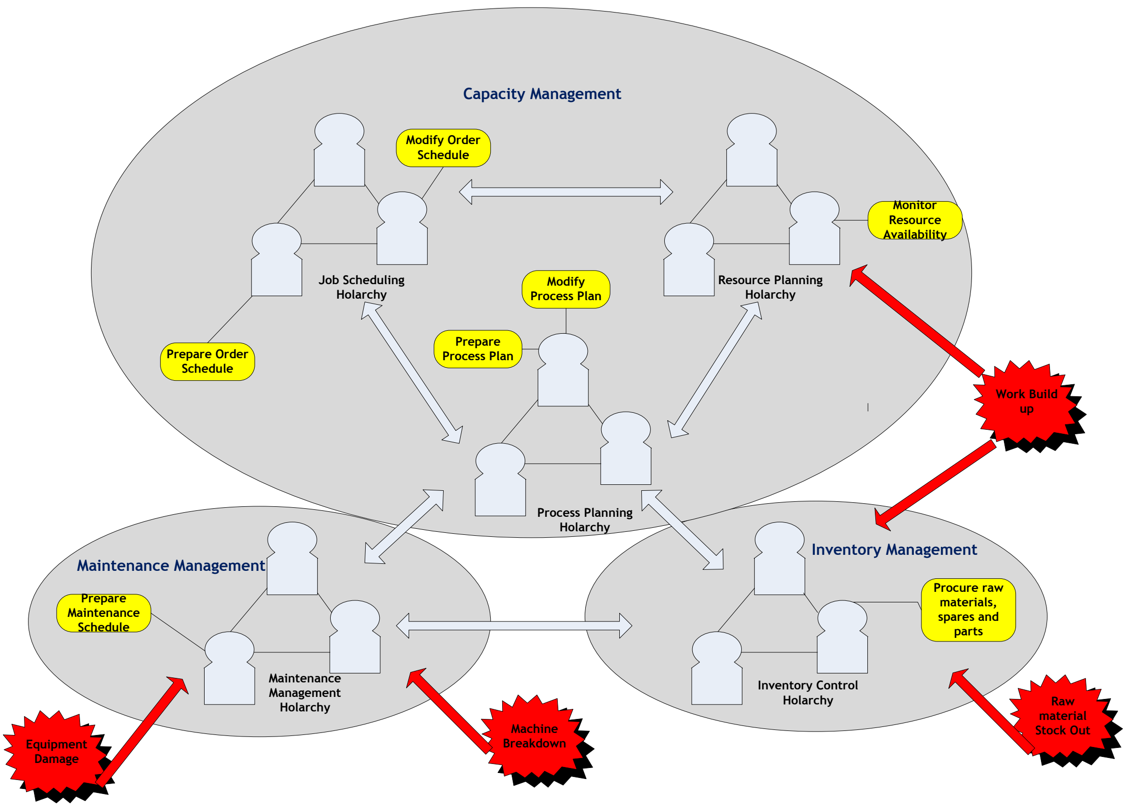

Figure 7: Holonic Control System Architecture

4.4.1 Inventory Control Holarchy

The purpose of this Holarchy is to manage and control raw material inventory so as to avoid the occurrence of stock outs during production. Four staff Holons which cooperate in this Holarchy are:

- **Supplier Holon (SH)**: the Holon represents the different possible suppliers for raw materials in the production chain. They supply information of the catalogue of products and their prices.
- **Purchasing Holon (PH)**: the Holon is responsible for procuring raw materials for an organization before stock outs occur. This is done by bidding different suppliers for the provision and selection of the best supplier option based on set criteria.
- **Inventory Level Holon (ILH)**: the Holon is responsible for monitoring the stock levels of each raw material. Once the reorder level of a raw materials and supplies is reached, the Inventory Level Holon communicates with Purchasing Holon to place an order from a supplier for replenishment.
- **Buffer Holon (BH)**: the Holon is responsible of checking an unanticipated sudden shortage of raw materials due to defective or contaminated raw materials resulting from poor operational procedures, poor storage or material handling techniques. When this occurs the Holon immediately updates the Inventory Level Holon on the sudden decrease in stocks.

4.4.2 Capacity Management Holarchies

The Capacity Management Function consists of three Holarchies which are the Resource Planning Holarchy, Process Planning Holarchy and the Job Scheduling Holarchy.

1. Resource Planning Holarchy

The purpose of this Holarchy is to monitor and manage the production resources which include machinery, equipment and transporters so as to maintain high levels of system availability. The Holarchy comprises of one basic Holon and two staff Holons which are:

- **Resource Holon (RH)**: this basic Holon represents the different machinery and equipment which are being utilized in the production process. This Holon will be directly connected to the set of physical equipment available on the shop floor in the different tool rooms using the system. In the case of a machine breakdown or maintenance procedure, the Holon renders itself unavailable.
- **Supervisor Holon (SH)**: this Staff Holon represents the operations manager’s role in a workshop. It has a bird’s eye view of the entire set of resources and processes.
- **Availability Holon (AH)**: this Staff Holon is responsible for constantly monitoring the availability of all the Resource Holons in the system so as to update the Supervisor Holon on the system status.

2. Process Planning Holarchy

The purpose of this Holarchy is to generate a real-time, optimal process plan for existing and new work orders. The Holarchy comprises of one basic Holon and two staff Holons which are:

- **Routing Holon (RH):** this Staff Holon is responsible for selecting the best sequence of operations for doing a job based on the current available resources. In the case of a sudden unavailability of a specific resource, the Holon receives communication from the Availability Holon and generates a new sequence. The same process occurs when more capacity is added (new Resource Holons are introduced).
- **Resource Holon (RH)**: this basic Holon represents the different machinery and equipment which are being utilized in the production process. It is the same Holon which is being utilised in the Capacity and Maintenance Management Holarchies. In

this Holarchy, the Resource Holon provides the Routing Holon with information on set of tasks and operations it can perform.

- **Availability Holon (FH)**: This Staff Holon also belongs to the Capacity and Maintenance Management Holarchies. In this Holarchy, the Availability Holon supplies the Routing Holon with information on the availability of system resources.
- **Bill of Materials Holon (BOMH)**: This Staff Holon computes the required raw materials to fulfil an order.

3. **Job scheduling Holarchy**

The purpose of this Holarchy is to generate a real-time, optimal job schedule for all existing and new work orders. The Holarchy comprises of two staff Holons and one basic Holon which are:

- **Scheduling Holon (SH):** This Staff Holon is responsible for generating the optimal job schedule based on the process plan supplied by the Routing Holon and information from the Bill of Material Holon. The Holon uses different set criteria to generate this schedule and updates the schedule in the case of any dynamic changes caused by rush orders or machine breakdowns.
- **Routing Holon (RH)**: this Staff Holon also belongs to the Process Planning Holarchy. It constantly updates the Scheduling Holon with information on the feasible process plans which can be implemented based on current system status. A change in the process plan results in an update of the job schedule.
- **Order Holon (OH)**: this basic Holon represents the work orders currently received from clients. This information is received from the system users and triggers the manufacturing process.

4.4.3 Maintenance Management Holarchy

The purpose of this Holarchy is to manage the consistent maintenance of system resources which include machinery, equipment and transporters so as to reduce the risk caused by wear and tear. The Holarchy comprises of one basic Holon and two staff Holons which are:

- **Maintenance Planner Holon (MPH):** this Staff Holon is responsible for conducting planning of scheduled maintenance procedures for the different existing system resources based on tool life and Mean-Time to failure data.
- **Resource Holon (RH)**: this basic Holon represents the different machinery and equipment which are being utilized in the production process. It is the same Holon which is being utilised in the Capacity Management Holarchy. In this Holarchy, the Resource Holon provides the Maintenance Planner Holon with information on Mean-Time-To-Failure and shelf life.
- **Availability Holon (FH)**: the Staff Holon also belongs to the Capacity Management Holarchy. In this Holarchy, the Availability Holon supplies the Maintenance Planner Holon with information on reasons why a resource is unavailable i.e. whether a machine breakdown has occurred or a machine is due for service.
- **Inventory Level Holon (ILH)**: the Holon is responsible for monitoring the stock levels of supplies (MROs- Maintenance Repair and Operating). Once the reorder level of a raw materials and supplies is reached, the Inventory Level Holon communicates with Purchasing Holon to place an order from a supplier for replenishment.

4.5 Implementation success factors

The design and installation of a Holonic Control System requires the existence of key enabling factors which support sustainability of the system. According to Christensen [19] some of the main success factors of implementing holonic systems and these are:

- Willingness for firms to decentralize operations: McFarlane and Bussmann [20] stated that a Holonic Manufacturing System supports the distributed manufacturing paradigm which depends on a decentralized architecture. Hence, firms which require Holonic Control Systems must be willing to decentralize their operations.
- Networking of production units through enterprise integration.
- Human integration through the adoption of computerized information systems: Most manufacturing systems are still adopting manual methods for their production planning and scheduling functions. Holons can only be utilized in computerized systems.
- Training and motivation to facilitate understanding on how to utilize the technology.
- System security to ensure protection of critical production information: Holonic Systems make use of the internet for transfer of information. Although the internet has immensely improved networking of business functions, a challenge still remains on how to adequately protect the information it carries and stores.
- Sustainability through the maintenance of a consistent power supply.

4.6 Implementation Barriers

Some South African Manufacturing firms still have operational obstacles they need to overcome to successfully implement Holonic Control Systems. These include:

- Adoption of new organizational structures: most firms in South Africa adopt a hierarchical structure with bureaucratic set of procedures. Such centralized structures do not support the holonic endeavour hence firms should aim to flatten their structures.
- Flexibility through adoption of new manufacturing technologies.
- The use of the internet for distributed manufacturing
- Automation of manufacturing functions
- Evolution from manual operational procedures to computerized systems

5 SIMULATION STUDY

It is critical to measure whether the proposed system improves the operational performance of Tool, Die and Mould-making firms. However the analysis of a distributed manufacturing system is not easily achievable with the range of activities involved in the different production units. Firms involved in distributed manufacturing are usually located in different geographical settings. To overcome this challenge, a simulation model which mimics the real system can be used as a tool to conduct numerical experiments.

A simulation-based test-bed for the firms in the tooling industry was developed so as to investigate the improvements the presented Holonic Control System architecture can cause. The test-bed consisted of two modules which are:

- Simulation Module: this module represents the operations taking place in different TDM firms.
- Holonic Control Module: this module implements the defined Holarchies.

The simulation model was created using the Rockwell ARENA Research version. The package was chosen because events like machine breakdowns, rush orders or failures can be modelled easily in ARENA. The holonic control module was developed in Java using the Java Agent Development framework (JADE). The holonic control module receives signals from the simulation model regarding order arrivals, machine failures and other events. Control signals are then transferred to the simulation model from the holonic module on how best to handle events occurring in the simulation model. The model logic together with its relationship to the holonic control module is illustrated in Figure 8.

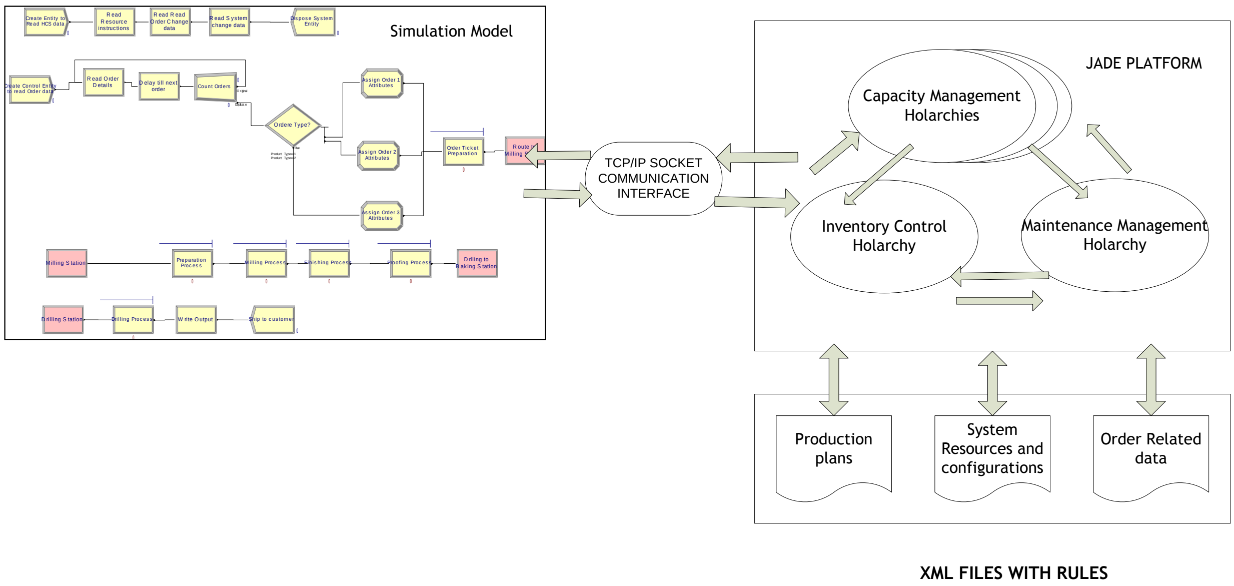

Figure 8: Simulation Model and HCS module

A comparison of results between the model without the holonic module (Model 1) and the simulation model connected to the holonic control module (Model 2) was done. The results are shown in Table 3. The throughput rates, system availability and uptime efficiency were significantly improved by using holons to manage operations.

Table 3: Summary of Results

Performance Measure	Model 1	Model 2
Throughput in 5 days	756 units	833 units
Uptime Efficiency	56%	78%
System Availability	45%	66%

The decision making algorithms for the holonic control system module is shown in Figure 9.

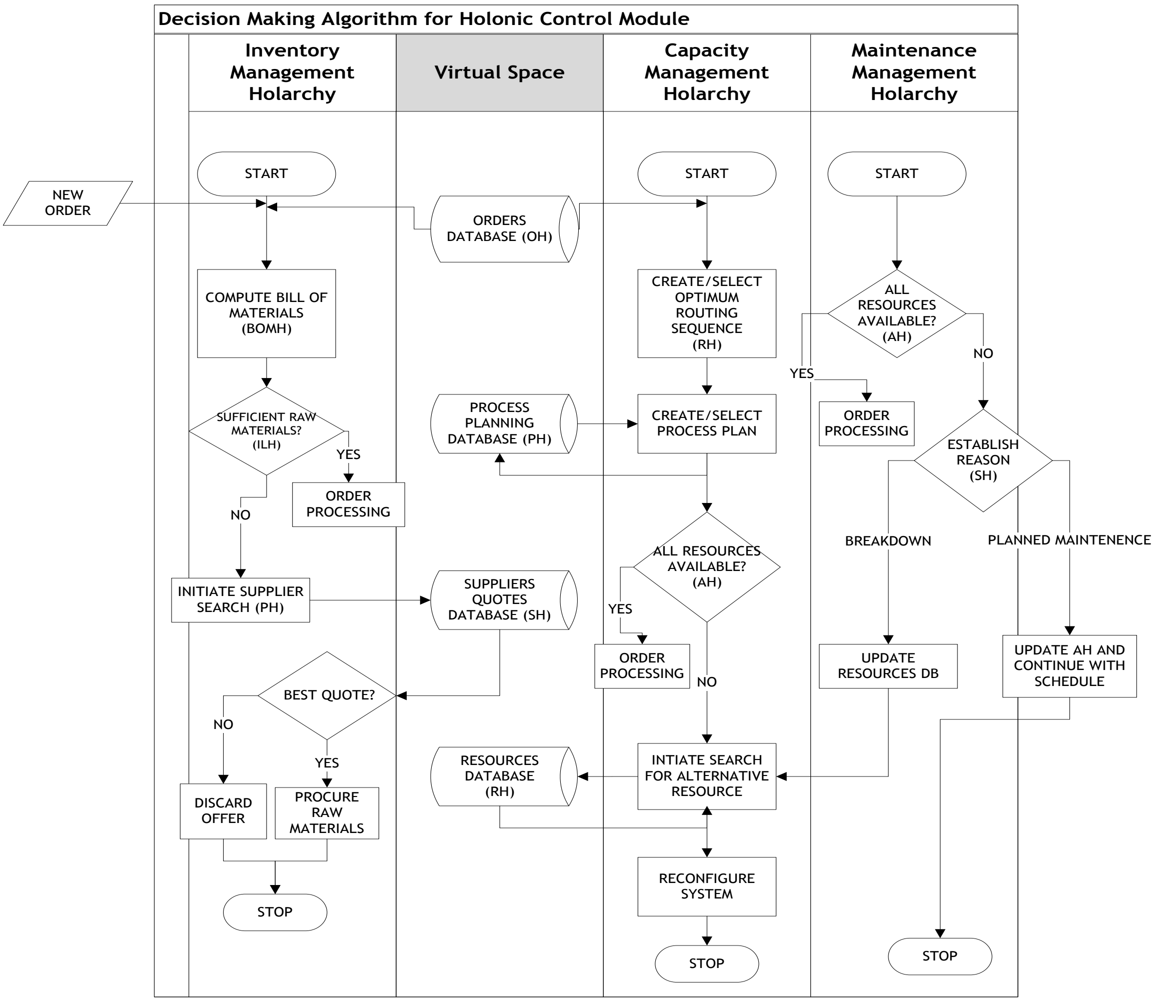

Figure 9: Decision making logic for HCS

6 CONCLUSION

Companies in the Tool, Die and Mould-making sector in South Africa can benefit from implementing Holonic Control Systems. This will enable them to withstand internal and external operational disturbances which occur during daily production and maintain high levels of system availability. The paper presented a proposed HCS architecture for the tooling industry in South Africa. Selected companies in the tooling industry belonging to the Western Cape Province of South Africa will be used for implementation and validation of the proposed system.

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