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A holonic workforce allocation model for labour-intensive manufacturing

Mozafar Saadat[1], Salman Saeidlou[1]* and Melissa C. L. Tan[1]

Abstract: This paper presents a new model for workforce allocation in labour-intensive industries. In such industries where production processes mostly include manual assembly operations, performance is highly influenced by the availability of skilled workers. Sudden unavailability of skilled labour has significant adverse effects on production. Furthermore, as competition intensifies, production becomes more sensitive to changing market demands. Such disturbances can be attenuated by introducing flexibility in the production planning process. Workforce allocation plays a significant role in the planning process. Thus, this paper focuses on workforce allocation, and a support system is developed from the concepts of holonic manufacturing systems and PROSA reference architecture. The system was designed in unified modelling language and was tested using an object-oriented software developed in C++. The use of the holonic methodology to develop the system has helped to identify the shortfalls of the conventional method adopted in industry and develop algorithms to improve the workforce allocation process. The proposed system was simulated using production data from a computer manufacturer case study. The paper then presents a comparison of the factory's conventional method of workforce allocation with the proposed holonic workforce allocation system. The results suggest an improved manufacturing throughput performance.

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Mozafar Saadat received the BSc (Hons.) degree in Mechanical Engineering from the University of Surrey, Surrey, UK, and the PhD degree in industrial automation from the University of Durham, Durham, UK. He has received various research funding in aerospace, automation and manufacturing industries, and published a wide range of peer-reviewed technical papers and editorial articles. He is currently with the Department of Mechanical Engineering, School of Engineering, University of Birmingham, Birmingham, UK, where he leads the Automation and Intelligent Manufacturing (AIM) Research Group.

PUBLIC INTEREST STATEMENT

A flexible and reliable allocation of workforce within a factory scheduling system is essential for the enterprise responsiveness to market volatility. Skilled human operators are considered as the core of the organisational structure in labour-intensive manufacturing. Furthermore, there are several factors affecting the allocation task such as employee's skills, their availability, flexible working hours and service demand. Therefore, the presence of a flexible and adaptable workforce allocation system is of great importance in all tiers of manufacturing supply chain. In the light of the above, we are addressing this crucial problem by introducing a novel framework based on the concept of intelligent manufacturing which offers operational advantages compared to conventional systems.

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1. Introduction

Inconsistent change and unpredictable disturbance cause difficulties for companies with regards to rapid response to customer demand. Smaller quantities of customised, individual, unique and single-identity products required by the customers make the case even harder and consequently a company, able to respond better and quicker, will gain competitive advantage (ElMaraghy, AlGeddawy, Azab, & ElMaraghy, 2012). Research effort in the field of manufacturing systems design continues to search for appropriate infrastructures to meet the challenges (Saadat, Tan, & Owliya, 2008; Sharifi & Zhang, 2000).

Flexible and adaptable scheduling on the shop floor plays an important role in achieving the required agility, while allocation of workforce to manufacturing jobs is a major part of the shop scheduling particularly in labour-intensive industries. Although people are generally more flexible than machinery, their resistance to change is still a problem to overcome (Maxwell, 1999) and can impede a quick response (James, 2002). A cross-trained or multi-skilled workforce has been cited as a way of providing labour flexibility and rapid response in operations reconfiguration (Bobrowski & Park, 1993; Wemmerlöv & Hyer, 1989). In a study by Easton (2014) a two stage stochastic program for cross-trained workforce scheduling is modelled based on service completion estimates and uncertain attendance and demand. The study pointed out that solutions based on the convolution estimates are more profitable and favour more cross-trained staff rather than specialists.

Nevertheless, possessing a flexible workforce also requires a workforce allocation (WA) system that is capable of responding rapidly to unexpected events, such as fluctuation in the order quantity or sudden unavailability of workers. In such cases, conventional practice is that the shop supervisor or production manager finds a substitute for the lost resource. The new workforce cannot necessarily attend to the job instantaneously, as labour will take time to adapt to a new system of work, and a period of acquaintance is normally required to catch up with the standard production rate. Furthermore, it is pointed out that there is uneasiness in the way in which professional managers use their intuition in place of scientific based methodologies, to perform workforce scheduling (Taleghani, 2010). The author advocates the need for more monitoring and control over the workforce scheduling process.

The role of workforce allocation has been shifting from rigid forecasting to providing a flexible organizational environment. A modern workforce allocation system on the shop floor aims at balancing supply and demand between labours and jobs and, at the same time, taking into account various parameters such as the labour's skills, and experience level. In addition, the system should be capable of taking proper measures in the event of a sudden unavailability of labour, which could have a significant impact on the production output. A systematic intelligent tool used to help make more precise and optimized decisions could make a difference. Castillo-Salazar, Landa-Silva, and Qu (2016) have done a comprehensive literature survey on workforce scheduling and routing problem alongside a study on the computational difficulties of solving these problems. They have considered different data sets and parameters that can affect the computational difficulties and has also reviewed the existing methodologies for solving these problems. Their suggestion includes mixed integer linear programming, meta-heuristics and hyper-heuristics.

In another study by Ighravwe and Oke (2014) the minimisation of the number of maintenance workforce is considered using branch and bound optimisation and non-linear integer programming. Although their study provides a tool for maintenance supervisors and managers to determine the optimal maintenance workforce size, it doesn't match the scalability and flexibility obtained by the proposed holonic system in this research.

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A study proposed the use of a web-based tool for dynamic job rotation, to respond swiftly to this type of disturbance (Michalos, Makris, & Mourtzis, 2011). The study compares well with the intentions of this paper, but their contributions aimed more at doing re-allocations to minimize operator related factors such as the repetitions of a task, equal distribution of fatigue, travelling distance of operators and increases in the match between competent operators and task requirements. In the light of the above, there is a clear gap in the literature as regards a dynamic workforce allocation system which monitors the consequences of labour reallocation on production.

Attia, Duquenne, and Le-Lann (2014) presented a mathematical model of a multi-skilled workforce allocation problem with flexible working hours following a genetic algorithm solver. The proposed evolutionary algorithm lacks scalability compared to the openness of a holonic system. Costa, Cappadonna, and Fichera (2014) considered the combinatorial optimisation of flow shop scheduling combined with skilled workforce allocation problem. The aim of the paper is to minimise the make span of the M-machine flow shop problem while considering the human factors. The results show a trade-off between make span and the workforce cost. Another study by Starkey, Hagras, Shakya, and Owusu (2016) made use of evolutionary algorithms for simultaneous optimisation of workforce skill sets and staff allocation. The work is comparable with other works implementing genetic algorithms to solve workforce allocation problem.

The aim of this research is to develop a system that can flexibly respond to change and disturbance. The Holonic manufacturing concept is considered to be a promising enabling concept due to its hierarchical and heterarchical approach, and which leads to both flexibility and stability (Jules, Saadat, & Saeidlou, 2013a, 2013b, 2015; Marik, Vyatkin, & Colombo, 2007; Saadat, Tan, & Owliya, 2010). This paper offers a practical approach to model workforce allocation in manufacturing based on holonic principles. An objected oriented approach is used instead of a database approach, to investigate the time dependent work-in-progress (WIP) where disturbances occur. WIP gives an additional vantage point to understand how the WIP self-regulates to compensate for the loss of throughput in order to maintain maximum throughput at months' end. Therefore, in Section 2, the holonic concept for the proposed system is explained. Section 3 presents details of the proposed workforce allocation system, where its architecture and data manipulation aspects are discussed. Sections 4 and 5 describe the system building, implementation and evaluation processes through an industrial case study. Finally, Section 6 concludes the paper.

2. Holonic workforce allocation concept

The Holonic Manufacturing System (HMS) originates from a philosophical theory of complex adaptive systems. It combines concepts of hierarchical systems and the integration of autonomous elements in heterarchical systems (Valckenaers & Van Brussel, 2015). In HMS, the hierarchical structure ensures cooperation among holons and guarantees the integrity of the system. The holons are subject to control from higher-level authorities, who aim to achieve a common objective or strategy. Conversely, a heterarchical structure allows the autonomic handling of tasks, through internal models and rules of behaviour embedded within a holon (Barbosa, Leitão, Adam, & Trentesaux, 2015).

Autonomy and co-operation are two distinctive features of holons. The former gives holon the stability to create and control the execution of its own plan and strategies without requirements for higher level assistance. The response of holons to a situation is the emergence of negotiation and cooperation among holons. Also, the similarity of the holons permits the reconfiguration of the system, where holons can be removed and added, without the need to adjust the overall structure (Van Brussel, 2014).

The proposed system in this paper is based on the PROSA (Product-Resource-Order-Staff holons) reference architecture (Van Brussel, Wyns, Valckenaers, Bongaerts, & Peeters, 1998) as shown in Figure 1. Such an approach properly addresses the inflexibility of the hierarchical systems (Leitão & Restivo, 2008).

The system generates workforce allocation plans using holonic concepts through workforce selection criteria, as summarised in Figure 2.

Figure 1. Relationship between PROSA and holonic workforce allocation system.
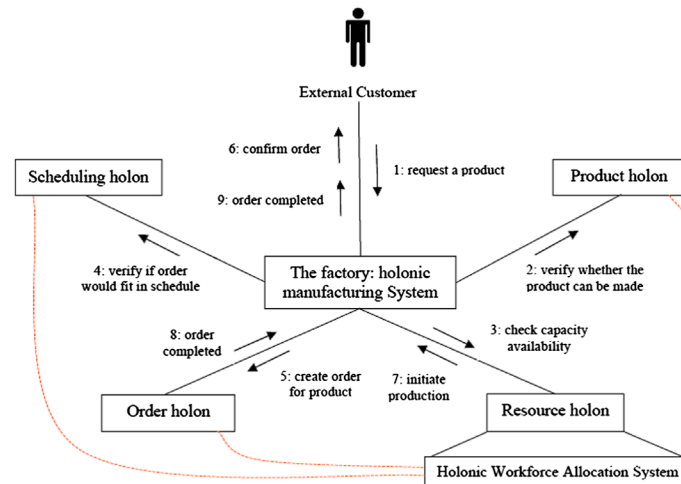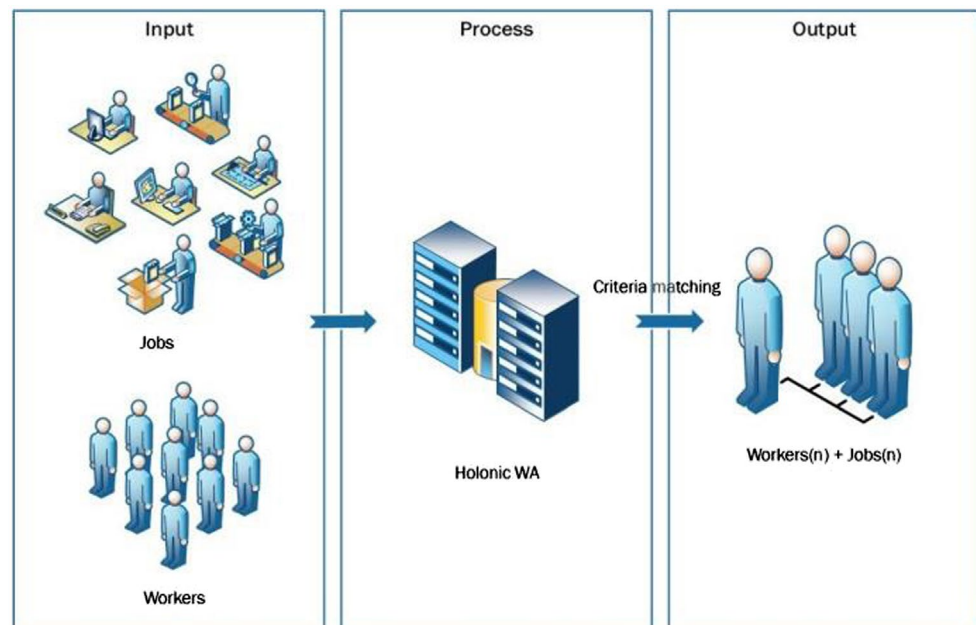

Figure 2. Holonic WA primary input—process—output.

Workforce is treated as a holon entity in the system. The holonic concept is an open hierarchical and heterarchical structure, which enables a worker to be added into the system without affecting the overall structure. It not only emphasises the supply and demand relationship between jobs and labours, but also integrates human resource (HR) elements including labours' skills and experience ratings.

3. Description of the proposed WA systems

The WA system is designed so that the order, product, manager, and labour holons provide inputs to the resource allocation (RA) module of the system. The RA module prepares and plans the allocation of workers to jobs. Workers, as labour holons, supply their availability, time constraints, skills and job experience as inputs to the RA module. RA conducts its allocation by utilising available resources and generates an assignment plan. As the workers are holonic, the autonomy elements enable them to bid for jobs according to their availabilty and attributes, while cooperative elements allow them to follow policies, rules, and requirements to comply with the order.

Figure 3. Shop floor WA system interactions inside HMS.
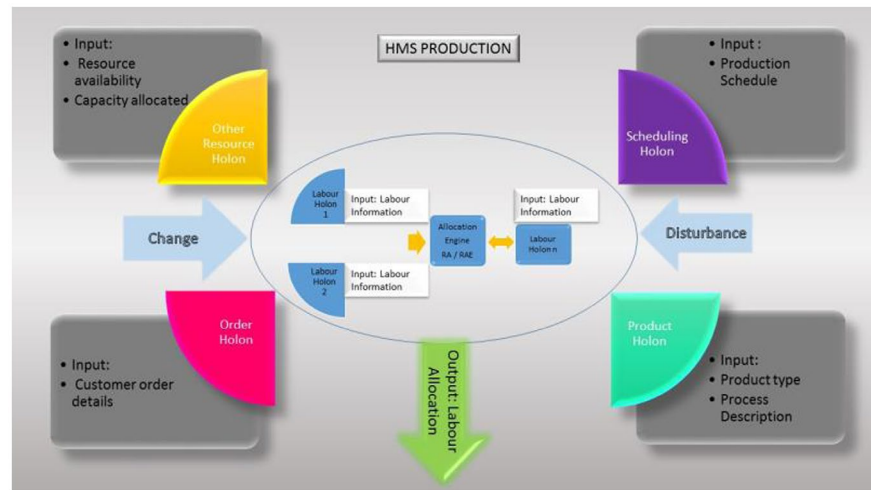
Resource Allocation Execution (RAE) is the other module of the system that executes the allocation plan produced by RA. However, it also identifies the real time status of the shop floor and makes necessary alterations to the plan to counteract any change or disturbance. When performing allocations, RA endeavours to find optimal solutions to the job allocation, while RAE performs online controlling and monitoring functions. If there are any sudden changes to the labour holon, RAE is notified about the status change so that further alternatives can be considered. RA and RAE communicate with each other in order to exchange schedules. The function of a workforce allocation system and interactions within the HMS are illustrated in Figure 3.

With regards to the system proposed in this paper, the following assumptions are made:

(1) All incoming jobs to the shop floor are firm customer orders, although they may change at a later date.

(2) There is no material shortage or delay.

(3) There is enough capacity (equipment, workspace, etc.) to produce the planned order.

The factory has a pool of labour available to it and that it holds information about the individual labour. The production line of each product type, which consists of 10 processes. There must be only one and only one labour selected for each process, and the selected labour will be part of the production line, satisfying and will satisfy the requirement of the process for experience and skill. Conventionally, if there is more than one suitable labour for a process, the first labour to satisfy the requirements is generally selected. If the algorithm is unsuccessful in finding a match, the RAE is then activated to carry out dynamic re-allocation of the available workforce.

The RAE system functions involve:

(1) monitoring the production line

(2) calling the part- time staff to replace absentees

(3) removal of idle labours from their workstation

(4) re-allocating the labour

(5) tracking the labour's movements

(6) generating a daily re-allocation plan

3.1. Monitoring the production line

The RAE system monitors the time-dependent state of the workstations such as disturbances, availability of idle labour, activity of workstations and the duration of the assembly and reallocation activities. The states of processes are monitored at regular time intervals.

3.2. Replacing absentees

The system allows part time and temporary labour to be introduced. The workers can accept or refuse to come to work if the request is at short notice. A worker is assumed to be able to come to work within a certain time, when called in at short notice. The shift time of the worker is relative to the station he/she will be working on. In the best case scenario, there are sufficient labours available to replace all absentees, and in the worst case, no extra labour is available.

3.3. Removal and reallocation of idle labour

The RAE detects workstations which have no preceding jobs and no work-in-progress and reallocates the workers on them. The workstations, which are waiting to be staffed, are given priority numbers based on the amount of work pending in front of workstations. Replacement labours are considered, together with those available for re-allocation. If no replacement labour is available, or in the event that replacement labours arrive in the meantime, the available unallocated labours are allocated dynamically.

3.4. Tracking labour movement

The RAE records the number of station repositioning incurred by the workers. Such movement is capped, due to the human factor of such activities.

3.5. Generating a daily reallocation plan

Assuming that the system is aware of the absences before production has started, the RAE is able to generate a labour reallocation plan for the whole production line until the moment that the replacement labours are signed in.

Algorithm 1 below represents the functions of the RAE system as explained above.

4. Software development of the model

Data flow in holonic WA is activated once a work order is generated. An order holon will be created for the new job, which contains product type, quantity, due time, and other respective information. The order holon requests product requirements from the product holon. The product holon provides a process plan and other technical data required for manufacturing the product. Labour criteria required is sent to the labour holon as a resource sub-holon that maintains data relating to available labour, and a log of activities. To implement the model, an object-oriented software is used that closely matches the holonic concept.

RAE coordinates local holons and communicates concurrently with them for work order requests, production capacity information and new events occurring on the shop floor. In the simulation, each workstation receives the parts required for each operation process before attempting to acquire labour. Labour is allocated according to the RA plan and moves to the designated workstation when it is requested. The allocated labours will stay with the workstation until the operation is completed, unless further rules are specified to prioritise labour operations. When jobs are completed, the holons update RA and RAE with their status and availability for the execution of ensuing orders. The WA system output is provided through a simulation package interface, and presents the results of production throughput on the shop floor. Figure 4 shows a UML class diagram of the holonic resource allocation system based on the reference model presented in Figure 3.

Figure 4. Object oriented system architecture of the proposed WA model.
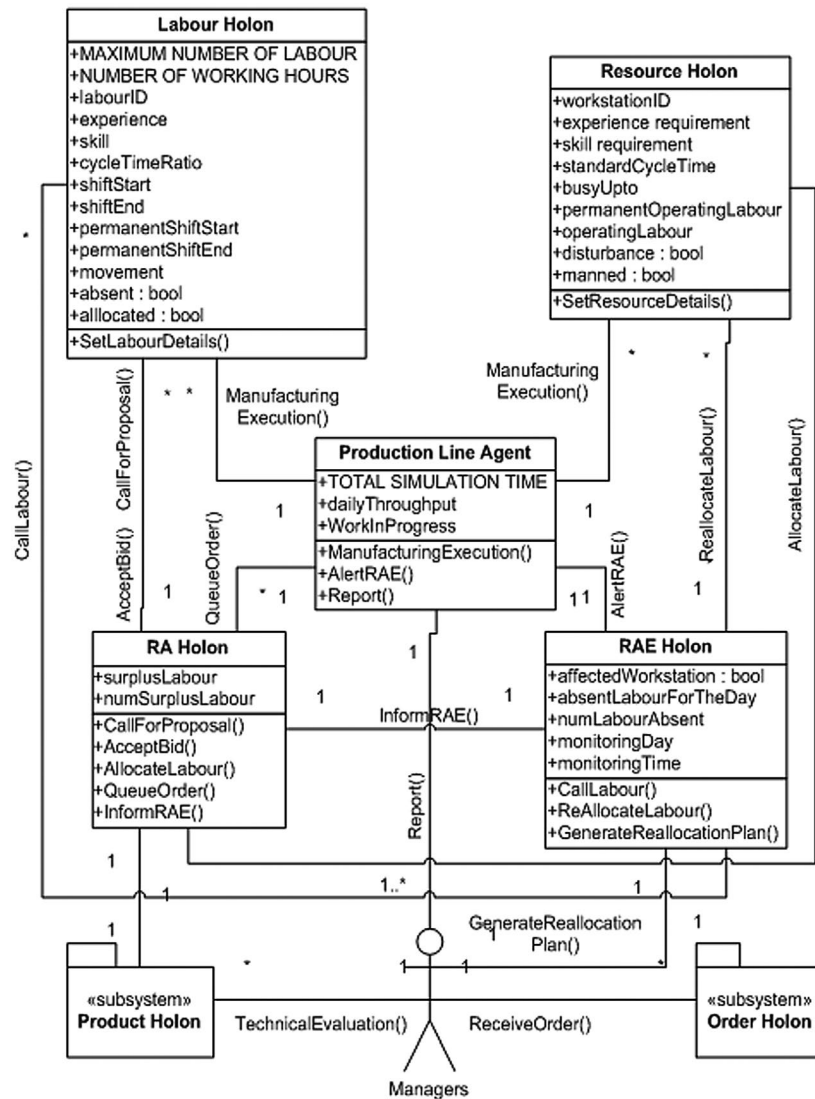
Algorithm 1 – Holonic resource allocation execution

For (number of workstation)

  If (work completed @ preceding workstation < {1, 18, 8})

    If (labour and current workstation is idle)

      If (labour movement <= human factor limit) {

        Unallocated labour on current workstation ()

        -> Labour allocated = FALSE

        -> Workstation manned = FALSE

        Go to next workstation

      End if

    End if

  End if

  If (work completed @ preceding workstation>= {1, 18, 8})

```
              Workstation priority = {10 to 1}
          End if
        End for
      For (number of absentees)
          Call surplus labour ()
      End for
      For (number of workstation, high to low priority)
          For (number of Labour)
              If (labour experience >= workstation req. experience)
                  If (labour skill >= workstation req. skill)
                      -> Labour allocated = TRUE
                          -> Workstation manned = TRUE
                      Count labour movement ()
                      Go to next workstation
                  End if
              End if
          End for
      End for
```

Figure 4 presents six distinct holons namely:

(1) Order holon, which represents the customers' account and the order specifications. It is represented in Figure 4 as a sub-system.

(2) Product holon, which instructs the RA holon as to which production line will be used. The holon also keeps the order holon informed of the rate of production and periodical throughput. If the order holon status changes, the product holon would alert the RAE holon.

(3) Resource allocation (RA) holon, which issues a call for proposals to the labour holon. The RA gathers information from the resource holon and through a concerted approach (referring to Algorithm 1), accepts the bids, ranks the bids, chooses the best bid and finalises the allocation process. When all processes have at least one labour pre-assigned, the holon updates the RAE holon and its role expires.

(4) Resource holon, which is a database of process information, skill/experience requirements and standard cycle times of the processes. Its goal is to have all its processes staffed. In the event of disturbances, for instance staff absences, the RAE holon is alerted by the resource holon.

(5) Labour holon, which is human and bids its abilities to the RA holon to secure a job on the production line.

(6) RAE holon, which is an adaptive RA holon alert to disturbances. When a disturbance occurs, the holon ensures that the overall throughput is maintained. It does so by negotiating for new labour to join the line, and coordinating the re-allocation process within the constraints of time and available resources.

5. Implementation through industrial case study

The case study was conducted at SYNNEX UK Ltd., which is part of a large global IT supply chain enterprise. The UK manufacturing plant caters for the original equipment manufacturers such as HP, IBM, Seagate, as an outsourcing partner and provides customised computer solutions. The factory has labour-intensive shop floors for assembling computer workstations, and it experiences a rather high rate of change and disturbance imposed on the production due to incoming orders or conditions of labours. Work orders are processed on a first-come-first-served basis except when a rush

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Table 1. Operation times of a product	
Operation time (min)	**Process**
2.1	WKSTN_1
1.9	WKSTN_2
1.1	WKSTN_3
2.5	WKSTN_4
6.2	TEST_1
240.0	TEST_2
1.3	TEST_3
2.2	TEST_4
2.7	TEST_5
2.0	PACKING
262	Total

order is received. In this section, the SynnexUK production is simulated by creating an order input for making a typical computer product as described below. Simulation experiment is then carried out for several scenarios.

The product has three general categories of processes: assembly, testing and pack-out. These are carried out in a total of 10 stations: four for assembly operations (W1 to W4), five for testing operations (W5 to W9), and one for pack-out as the final process (W10). According to the actual shop floor layout, a buffer of two units is used before each assembly workstation (W1 to W4) in the simulation model. W6 is an unstaffed operation, therefore there would be no labour allocated to it. Once assembly is completed, the product is placed onto a trolley for the first and second tests, which are carried out in batches of 18. The third test is carried out individually, and the fourth test is conducted in batches of eight. Operation times for different processes of this product are given in Table 1.

According to the production processes specified earlier, a list of criteria ratings for each process is created based on the subjective evaluation of the processes. Table 2 summarises the list of criteria ratings used in the simulation model according to the company's production management decision. This, in turn, is based on the characteristics and complexity level of the operations to be performed. The capability of an individual to perform an operation is based on skill. The rating consists of three values: zero, one, and two, and these represents no experience, a training phase, and fully trained conditions respectively. Experience is expressed as a percentage, and relates to the number of occasions a specified labour has performed the job since his/her employment begun.

Table 2. Criteria ratings list of processes for a product		
Production processes	**Skill**	**Experience (%)**
WKSTN_1	0, 1, 2	≥50
WKSTN_2	0, 1, 2	≥50
WKSTN_3	0, 1, 2	≥50
WKSTN_4	0, 1, 2	≥60
TEST_1	2	≥80
TEST_3	2	≥80
TEST_4	2	≥80
TEST_5	1, 2	≥60
PACKING	1, 2	≥50

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It is assumed reasonable that a replacement labour will sign in to work within two hours of being called in and that a worker will take five minutes to switch stations and to become fully effective on the workstation. A worker may be reallocated a maximum of 12 times. A work input rate of three units every 16 min, is judged to generate results close to the data of the case study. Twenty labours, permanent and temporary, were available with at least one available for each process.

6. Results

The experiment was carried out on object-oriented software written in C++. The allocation system was simulated for a discrete event production scenario, for a total time of 43,200 min (30 days). Simulations were carried out in the context of five scenarios as presented below. The experiment tests two methods of labour allocation namely the Conventional Allocation Method (CAM) and the Holonic Workforce Allocation Method (HWAM). The results of the experiments are shown in the following section. This section presents five different scenarios where the conventional allocation method (CAM) and the holonic workforce allocation method are put to the test. The results in terms of the daily throughput are shown in Figures 5 and 6. Daily work-in-progress is illustrated in Figures 7 and 8, and monthly throughput of the production line is depicted in Figure 9.

6.1. Base scenario
Disturbance: No disturbances, Decision model used: Holonic and Conventional Allocation; Average work-in-progress: 13, Total Throughput: 2680.

6.2. Scenario 1
Disturbance: Labour absent on workstation 1 on Day 1 without replacement; Average work-in-progress: 13 for HWAM, 13.5 for CAM; Total Throughput: 2680 for HWAM, 2592 for CAM.

6.3. Scenario 2
Disturbance: Labour absent on workstation 1 on Day 1 with replacement; Average work-in-process: 13 for HWAM, 15 for CAM; Total Output: 2680 for HWAM, 2592 for CAM.

6.4. Scenario 3
Disturbance: Labour absent on workstations 1, 2, 3 on Days 1, 2, 3 and on workstations 7, 8, 9 on Days 4, 5, 6 without replacement; Average work-in-process: 16 for HWAM, 12.5 for CAM; Total Throughput: 2680 for HWAM), 2408 for CAM.

6.5. Scenario 4
Disturbance: Labour absent on workstations 1, 8 on Days 15, 16, 17 and on workstations 7, 5 on Days 18, 19, 20 without replacement; Average work-in-process: 18 for HWAM, 57 for CAM; Total Throughput: 2680 for HWAM, 2280 for CAM.

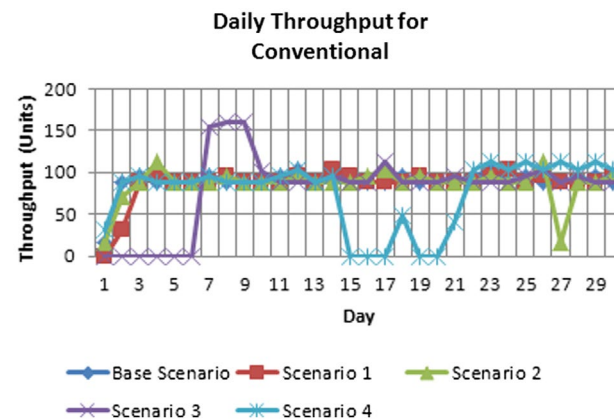**Figure 5. Daily throughput results of all scenarios for CAM.**

Figure 6. Daily throughput results of all scenarios for HWAM.
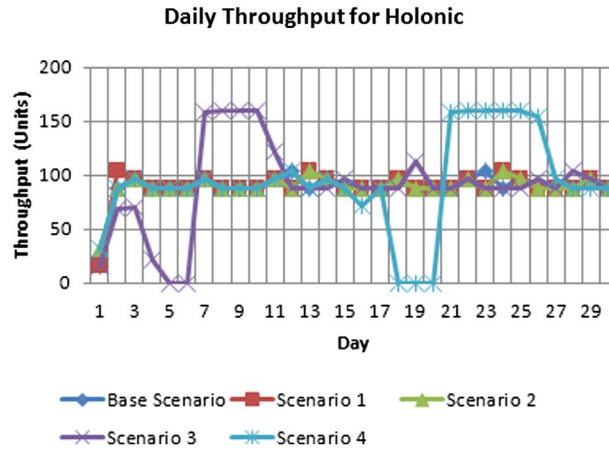

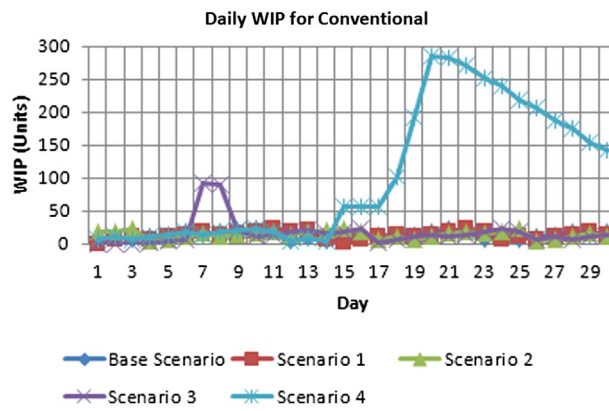**Figure 7. Daily throughput results of all scenarios for CAM.**

Figure 8. Daily throughput results of all scenarios for HWAM.
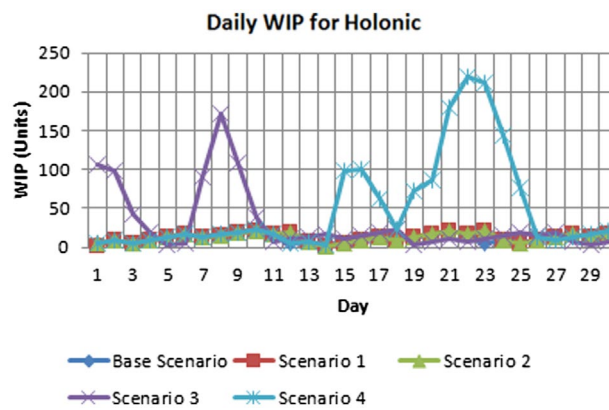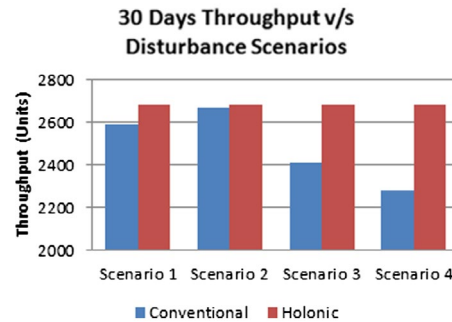
Figure 9. Total throughput results of all scenarios for CAM and HWAM.

7. Discussion

When there is no disturbance, as in the base scenario, the 30 days throughput cycle lasts for a period of 13 days, as shown in Figures 5 and 6 for the base scenario. When there is no disturbance, the workforce allocation plan is simple. Peaks and troughs can be predicted with good accuracy to prepare infrastructure for production. Also seen in Figures 7 and 8 is that the work-in-process cycle lasts for a period of 23 days; the WIP is low which means little queueing and more efficient use of labour. Both the CAM and HWAM produced the maximum total throughput over 30 days.

When there are disturbances, as in scenario 1, CAM has an allocation plan which is not suitable for the disturbance and gives a new throughput cycle lasting an undefined period. On the other hand, HWAM yields an allocation plan that gives a new throughput cycle lasting a period of 15 days as shown in Figure 6. This means that HWAM absorbed the disturbance early, while CAM has been slower to respond (see Figure 5). Referring to Figures 7 and 8, CAM yields a WIP cycle which lags behind that of HWAM by one day, which explains the loss of throughput. By comparing the graphs for scenario 1 in Figures 5 and 6, a surge in daily throughput can be noted, on the second day of production. The allocation plan from the HWAM, encourages the workforce to compensate on the following day, for the loss of WIP on the day of the disturbance. Conversely, CAM did not respond quickly and pro-actively enough in order to maintain the best throughput.

In scenario 2, due to the time delay for the replacement labour to get acquainted with the work, the production line did not have enough time to convert WIP to throughput, so the CAM lost throughput during that day. HWAM, however, managed to remove the disturbance subtly, so that the throughput and WIP graphs of the base scenario and scenario 2, in Figures 6 and 8 respectively, for HWAM, is almost the same. The allocation plan, from HWAM, called for the dynamic reallocation of the workforce until the replacement labour arrived. This helped to maintain the maximum throughput.

In scenario 3, the disturbances are so severe that CAM could not respond effectively and the throughput, on the days of the disturbance, was nil. HWAM has enabled production by the dynamic reallocation of available idle labour. On day 8, HWAM compensates the production by producing more WIP to buffer, as shown in Figure 8. The stock allowed the production line to continue for an extra day at maximum daily throughput, as shown in Figure 6, as compared to Figure 5 (days 7–10).

In scenario 4, the HWAM allocation plan has encouraged the labour to deplete the WIP swiftly while maintaining the optimal throughput, as shown by the high rate of decrease of WIP in Figure 8.

HWAM has outperformed the CAM on all scenarios, as shown in Figure 9. The holonic concept has enabled the modelling of the production line and helped to identify the problem and to develop the algorithms that make the HWAM resilient to disturbances.

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8. Conclusion

This paper describes the use of principles of holonic manufacturing concept to model a production line. An object-oriented simulation software was developed based on the characteristics of a labour-intensive manufacturing environment, where labour unavailability had a significant effect on the throughput. A new model of workforce allocation was designed using the PROSA architecture which enabled improvements to be made to the conventional model. Discrete-event simulation was used to demonstrate the performance of the model against conventional allocation methods using real industrial production data. The results of the system simulation showed that the conventional decisions, based on management experience to allocate labour, could not maintain the optimal production throughput. This is in stark contrast with the results from the proposed holonic model relating to the same disturbance, where the loss in throughput was contained and reasonably reduced. In this paper, the daily throughput and work-in-process of the production line are studied. Patterns are identified and used to explain the emergence of intelligence within the holonic system to maximise the total throughput. The results suggest that workforce allocation models based on holonic manufacturing principles offer significant potential to improve performance in modelling and improving production in labour-intensive industries.

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