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A Combination of Workforce Sizing Plan and Worker Selection Guide with the Holonic Control Paradigm

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Abstract

The Holonic Workforce Allocation Model (HWM) is a dual-level advisory model using the concepts of Holonic Manufacturing Systems (HMS). The quantitative and pre-active level is termed as Workforce Sizing Plan (WOZIP), whereby the number of workers required for a production period can be forecasted. The resultant group of workers, in a case-by-case fashion, are continually assigned to parallel series of production tasks considering the individual skill and task urgency factors, at the qualitative and reactive level called Worker Selection Guide (WOSEG). When developing such an integrated model, four holonic control attributes need to be observed, namely real-time control, event-driven control, intelligent control, and distributed control. These control attributes help ensure the effective and sustainable improvement of factory processes, for which the strengths of and the interactions between holonic elements are discussed in this paper.

Keywords: Holonic control, workforce sizing, worker selection

1. Introduction

The chronicle of the author's research is first introduced. The preliminary ideas of HWM were framed in Lim *et al.* (2008) and Lim & Chin (2008), through which a holonic approach was proposed to cope with labour absenteeism and turnover. On top of a host of build-ups and fine-tunes, the complete model was presented in Lim (2011a) with a sound architecture and comprehensive algorithms, and was experimented using mock-up data and computer simulation. For separate presentations, the HWM has been split into WOZIP (Lim 2011b) and WOSEG (Lim & Chin 2011a; Lim & Chin 2011b). The WOZIP, with the aid of exponential smoothing, is designed to periodically estimate the number of workers required in job-shop production. The WOSEG, as a complement, picks the best-suited worker for each scheduled task. It takes both the worker skills and task urgencies into account, so as to allow cross-training opportunities (i.e. for long-term flexibility) besides fulfilling specialisation requirements (i.e. for short-term productivity).

The term "holonic" is derived from "holon", as brought up in nineteen-sixties by a Hungarian philosopher Arthur Koestler, in his book titled *The Ghost in the Machine* (Koestler 1967). "Holon" is rooted from the Greek *holos* meaning *whole* and the suffix *–on* meaning a *particle* or *part*, and was initially meant to describe a basic unit of biological and social organisations. That idea, however, was borrowed by a reputed manufacturing research programme of the early nineties, namely Intelligent Manufacturing Systems (IMS). The IMS programme was internationally established in 1993-1994, owing to the partnership between the European Community (EC), European Free Trade Association (EFTA), Australia, Canada, Japan, and the United States (US). Among the six major projects proposed in this programme, the fifth one was termed as "Holonic Manufacturing Systems: system components of autonomous modules and their distributed control", with an acronym HMS.

Over the four years of feasibility study, the HMS became one of the fully endorsed IMS projects in 1997; therefore, the International HMS Consortium was formed in the same year and was dedicated to translate the relevant findings of Koestler into a set of novel concepts, suitable for the sustainable development of manufacturing industries. The mentioned strengths of holons include the adaptability to changes, the efficient use of available resources, and the stability in face of disturbances (Valckenaers *et al.* 1997; Bongaerts 1998). A list of holonic definitions was provided as follows:

Holon : An autonomous and cooperative building block of a system for transforming, transporting, storing and/or validating information and physical objects. The holon consists of an information processing part and often a physical processing part. A holon can be part of another holon.

Autonomy : The capability of an entity to create and control the execution of its own plans and/or strategies.

Cooperation : A process whereby a set of entities develops mutually acceptable plans and executes these plans.

Holarchy : A system of holons that can cooperate to achieve a goal or objective. The holarchy defines the basic rules for cooperation of the holons and thereby limits their autonomy.

HMS : A holarchy that integrates the entire range of manufacturing activities from order booking through design, production, and marketing to realise the agile manufacturing enterprise.

Towards materialising the autonomous and cooperative elements, Balasubramanian *et al.* (2001) addressed four requirements for holonic systems control, inclusive of real-time control, event-driven control, intelligent control, and distributed control. In HWM, the first two control attributes are paired up and applied to information processing, while the other two are meant for the sizing and selection procedures, a.k.a. the implementation of WOZIP and WOSEG. See Figure 1.

2. Computational Scheme

The computational scheme of HWM is divided into three parts: the input information, the algorithm of WOZIP, and the algorithm of WOSEG. See the block diagram in Figure 2.

2.1 Input Information

The input information relates to the data flow of various tasks and workers:

2.1.1 Task Processing Time, $t_{pro,i}$

For a certain type of task *i*, the processing time can be estimated via time study. It is normally distributed and prorated based on the customer order quantity and the inherent production variability.

2.1.2 Task Urgency, C_i

The allowable time, $t_{all,i}$ for a task is the difference between its arrival time and due time. Any task that spends more than its allowable time is considered overdue. The urgency of task *i* is computed as the ratio of processing time to allowable time:

$$C_i = \frac{t_{pro,i}}{t_{all,i}} \tag{1}$$

2.1.3 Worker Availability, A_j

A worker is considered available (A_j = 1) only if he is idling or has finished his previous task; otherwise, the worker may be absent (A_j = 0) or have resigned (A_j = -1) from the workplace or be engaged in any current task (A_j = 2).

2.1.4 Worker Skill Rating, $S_{i,j}$

The skill *i* held by worker *j* can be rated in the light of Learning Curve:

$$S_{i,j} = 1 - N_{att(i,j)}^{\frac{\log \kappa}{\log 2}} \tag{2}$$

Where, κ represents the learning rate ($\kappa < 1$) and $N_{att(i,j)}$ is the number of attempts (N $\geq$ 1) of worker *j* on task *i*.

2.2 *Workforce Sizing Algorithm*

In order to avoid the redundancy of workforce, as well as to nullify the adverse effects of turnover and absenteeism, the WOZIP optimises the number of workers for any production period *t*. With this purpose, the machine utilisation, *U*, the workforce disturbance, δ, and their idling rate, χ of the past period *t-1* are taken into account. Exponential smoothing is used to predict the upcoming values of these variables. The general equation:

$$F_t = F_{t-1} + \alpha\,(Y_{t-1} - F_{t-1}) \tag{3}$$

Where, *F* and *Y* respectively denote the forecast value and the actual value of each variable considered, and the symbol α is the user-defined smoothing constant.

To determine the required workforce size, $N_{W,t}$, the formulation of WOZIP is associated with the number of working machines, N_M, and the user-defined maximum utilisation, U_{max}:

$$N_{W,t} = N_M\left(\frac{U_t + \delta_t}{U_{max}} - \chi_t\right) \tag{4}$$

2.3 *Worker Selection Algorithm*

For the WOSEG to pick available worker *j* for task *i*, the "picking index", $\Pi_{i,j}$, is formulated upon the required skill, $S_{i,j}$, and the mean of the other skills held by worker *j*, $\bar{S}_{i:oth,j}$; the skill gap between the minimum, $S_{i,min}$, and maximum, $S_{i,max}$, of all the workers; a random number, *R* ($0 \leq R \leq 1$); the task urgency, C_i, and the user-defined mean urgency, C_{mean}:

$$\Pi_{i,j} = C_i\,S_{i,j} + \frac{R(S_{i,max} - S_{i,min})}{2\,C_i} + (C_i - C_{mean})(S_{i,j} - \bar{S}_{i:oth,j}) \tag{5}$$

For an incoming task *i*, the picking index associated with each available worker is computed. In the end of the loop, the matching with the highest picking index is carried out.

The rationales of the above procedures and formulas have been explicated in Lim (2011a).

3. Holonic Control Description

The tasks and workers (i.e. human operators) are classified as two heterogeneous holons in the holarchy of HWM, wherein a supervisory holon is added so as to resemble the real production. Such arrangements adhere to the Adaptive Holonic Control Architecture (ADACOR) of Leitão & Restivo (2007). The holonic terminology:

Task Holon (TH) : Production orders launched, carrying all information of tasks.

Operational Holon (OH) : Operators or physical resources, possessing a set of skills.

Supervisory Holon (SH) : Supervisors, who coordinate and optimise the production.

These main holons put the heterogeneous sub-holons, namely tasks (h_T), workers or human operators (h_O), and supervisors (h_S) under their respective function shells. See Figure 3.

A control structure built up with holons is called holarchy. According to Yuen (1999), every holon must be equipped with an information processor, and thus, *data storage* is at the very core of a holon or holarchy. For WOZIP, a holarchy made up of the TH, OH, database holon (DH), forecasting holon (FH), and sizing holon (ZH) is presented in Figure 4; and for WOSEG, the interactions between TH, OH, SH, DH, and picking holon (PH) are shown in Figure 5.

With reference to the HWM control requirements, the real-time and event-driven control is explained in *3.1*, after which the intelligent and distributed control is elaborated in *3.2*. Subsequently, in *3.3*, the holonic strengths exhibited by HWM are reviewed.

3.1 Real-time & Event-driven Control

Stankovic (1988) claimed that the correctness of a system depends not only on the logicalness of results, but also on the time at which the results are generated. Hence, the HWM and its reactive branch WOSEG must be capable of processing the input data upon the arrival of a task, so as to assign a worker to the task in a lively and reliable fashion using Eqs. (1), (2) and (5). Once the worker-task matching is reached, the holons will automatically update the relevant information: TH updates the task information of all its sub-holons, and the same for OH. By the control of OH, once a worker attends to a task, his availability is set to “busy”; and when he finishes the task, his availability returns to “idle” and his skill rating is increased as per the Eq. (2). Meanwhile, TH provides information to the entire holarchy about the task urgency, start and finish times. All such updates also need to be timely and referable for the next matching decision.

Every arrival of task, assignment of worker, occurrence of disturbance, or end of a disturbance is treated as event. For a real-time holonic organisation, the information update is triggered once an event takes place. Under the event-driven control, holons may react to events and thereby incur changes of status in a flexible manner without following a rigid set of rules and regulations. The event-driven control can be used to describe the dynamic behaviour of holons, to the extent that their action plans are developed and executed through the occurrence or non-occurrence of certain events.

3.2 Intelligent & Distributed Control

The intelligent and distributed control is important to make a holonic system reconfigurable and adaptive to changes. A system component that uses intelligent control is expected to be able to accomplish its specific task in the presence of uncertainty and variability in its environment (Parker 2003). In practical terms, intelligent control can help resolve problems, identify objects, or plan a strategy for a complicated function of a system (Cai 1997). A significant example of intelligent control in our daily life is the *anti-skid brake system* for motor vehicles.

At the pre-active level of HWM, namely the WOZIP, some variable data items are inputted from TH (i.e. number of machines and rate of utilisation) and OH (i.e. number of workers, disturbance and idling rates). These variables are used in Eqs. (3) and (4), which lead to the optimum number of workers. Furthermore, at the reactive level WOSEG, the cross-training strategy associated with Eq. (5) plays a significant part in judging which worker attends to which task. The above series of formulas constitute the intelligent control for the HWM to take effect.

For distributed control (i.e. decentralisation), the system components each with its own function are flexibly connected instead of relying on a centralised regulator. This is for the convenience of integrated data acquisition, dynamic behavioural control, and decision-making application (Hardy-Vallée 2007). On the basis of distributed control, every holon of TH, OH and SH is a decision-making entity for the WOSEG. The authority given to the respective entities is not fixed but interchangeable among others in different situations. There are three possible assumable situations in job-shop production: *normal production, rise of severe abnormality*, and *worker idling*. Once a situation has changed into another, the decision-making roles will be switched in tandem among these three holons, as shown in Table 1:

Table 1. Holons as Situational Decision-makers

Situation \ **Decision-maker**	Primary (Initiative)	Secondary (Supportive)	Tertiary (Assistive)
Normal Production	TH	OH	SH
Rise of Severe Abnormality	SH	OH	TH
Worker Idling	OH	TH	SH

In either situation, the designated primary decision-maker has relatively greater autonomy to initiate the worker-task matching decisions. Every decision initiated, however, needs to be accepted or supported by the secondary holon, for the sake of cooperation. In other words, negotiation is possibly raised between these two holons in finalising a decision. From the point of view of multi-agent systems, negotiation is known as the convergence of various solutions through compromise and communication (Davis & Smith 1983). Since the decision-making power of the tertiary level holon is significantly less, it will only follow or assist in whatever decisions made, unless there is a special or occasional need for its decision.

Succinctly, the intelligent and distributed control of HWM can help a user figure out "how many to hire, which situation, what to do, and who will do". The decision-making styles for different situations and the changeable forms of communication between holons are narrated as below:

3.2.1 Normal Production

Normal production implies a situation in which tasks are handled by operators as planned. Even though disturbances arise from time to time, their impact may be duly absorbed as well as overcome by the pre-active and reactive holons. The production work is considered reliable and capable of receiving inputs (e.g. raw parts or tasks) and delivering outputs (e.g. final products), as long as the productivity baseline is met. The TH and OH are able to exchange their information and continue the production with minimal SH intervention. The SH, on a standby mode, appears passive in this situation.

The OH provides information to the TH of the workforce availabilities and skill levels in a *bidding* fashion. Meanwhile, the TH makes use of Eqs. (1), (2) and (5) to form a "contract" on each incoming task (i.e. pick a best-suited worker). In the context of auction-based methods (Haque *et al.* 2008), the OH is effectively the "seller agent" that provides the information of its resources (i.e. workers) to the "buyer agent" TH, which determines the way to assign the workers.

Nevertheless, the contract formed by TH is not absolute and is later opened for the affected human operators under OH (i.e. secondary decision-maker) to accept or reject it. This stage is effectively the negotiation stage allowing those workers to express their own preferences. In essence, the autonomy or negotiation power of any holon at this stage would be regulated through the cooperation between homogeneous (i.e. workers only) or heterogeneous holons (i.e. OH and TH).

3.2.2 Rise of Severe Abnormality

Severe abnormality means the under-productivity or derailment of factory processes, which can be seen from a great number of tasks unattended and overdue. A threshold may be given to determine the rise of such situation, for example, the productivity falls below 70% baseline or the overdue rate exceeds 20% critical limit. At this point, the *bid-and-pick* interactions between OH and TH seem ineffective and the intervention of SH is triggered to take over the situation.

To remediate the under-productivity, SH is in charge of both the pre-active planning and reactive selection. In spite of the normal procedures of WOZIP and WOSEG, an authorised supervisor (i.e. under SH) may adjust the task orders (i.e. under TH) or instruct the operators (i.e. under OH) on alternative plans such as working overtime hours, bringing in more resources, resetting production plans, delaying some deliveries, etc. Negotiation between SH and OH is permitted but the extent of negotiation is governed by SH. The intervention of SH may continue until the performance is back to normal.

3.2.3 Worker Idling

Worker idling occurs whenever a human operator finishes the task on hand and is waiting for the next task to arrive. In this waiting period, the worker can choose to assist in one of the unfinished tasks, especially those that are already or potentially overdue. The choice of such assistance is based on the task information and the worker self-awareness. The *bid-and-pick* process between OH and TH is reversed from that of the normal production and is based on the same set of data. In this situation, the SH is also on standby, being passive, and causes minimal intervention to the other holons.

Such mechanism is intended to make use of under-utilised resources to ensure each idling one to find a task to perform (Smith 1980). The worker involved may be rewarded for his dedication as more experience and skill points are gained. Personal judgments and preferences have also become more salient in this situation because the autonomy of idling workers is largely increased, that is, they are free to choose whichever tasks they might render assistance to. None the less, it is important to realise that the concern of the larger whole (i.e. holarchy or factory) is to reduce the amount of overdue tasks and enhance the overall performance.

3.3 Holonic Strengths

This section manifests the holonic strengths leading to the success and sustainability of HWM in terms of autonomy and cooperation, information carrier, disturbance survivor, hierarchy-heterarchy combiner, and new management style:

3.3.1 Autonomy and Cooperation

Autonomy and cooperation constitute the minimum set of the holonic attributes. For HWM, the informative and managerial formulas derived in *2.1–2.3* are autonomously executed by OH and TH. The degree of autonomy is dependent on the holon's decision-making level in a certain situation (Table 1), and yet, there is no strict command from the primary level to the secondary level and so on. Being subject to the goals of the overall system, the autonomy of a holon is hinged upon the cooperation between oneself and the others. With this understanding, the role and position of each holon in HWM can be ascertained and over time reconfigured through the dynamic communication between holons.

3.3.2 Information Carrier

A holon by itself is a functional unit serving the overall system which it belongs to. In sign of certain functions, every holon ought to have an information processor that is usually a data storage (Yuen 1999). Within HWM, the task information and the workforce information are respectively processed by TH and OH when the production is in progress. These pieces of information are variable, updatable, recordable into and retrievable from a database system, whereas they are required for WOZIP and WOSEG to accomplish the pre-active planning and reactive picking decisions.

3.3.3 Disturbance Survivor

Absenteeism and turnover are identified as the major disturbances in labour-intensive manufacturing. Therefore, the development of HWM was aimed at resolving their impact. At the pre-active level WOZIP, the disturbance rate is one of the parameters used in optimising the workforce size, that is, a greater disturbance rate will signal the Eq. (4) to make a request for more workers to revamp or maintain the productivity. In succession to such a countermeasure, the cross-training chances given by the reactive level WOSEG are intended to help promote long-term workforce flexibility through widening the overall skill spectra, with which unattended tasks can be handled more efficiently and punctually.

In general terms, a holonic organisation is able to survive disturbances by the nature of being stable, flexible, and adaptive to environments. Even when some holons are destroyed, the holarchy itself, thanks to the real-time and event-driven control, can quickly recognise bottlenecks and reroute its components to resume the production using the remaining assets (Fletcher & Hughes 2006).

3.3.4 Hierarchy-Heterarchy Combiner

Holonic architecture is said to have combined the best features of hierarchical (i.e. top-down, commanding) and heterarchical (i.e. bottom-up, cooperative) organisational structures (Bongaerts 1998). A holarchy can quickly decompose and recompose itself in the changing environment, due to the fact that it is built on a behavioural policy instead of a structural or hardware oriented policy (McFarlane 1995). Thus, shifting responsibilities up and down the holarchy is seen as the effective way to secure high efficiency in repetitive situations as well as great adaptability towards new circumstances (Wyns 1999).

In this research, the decision-making authority of the holarchy (i.e. HWM) is delegated to its constituent holons (i.e. TH, OH and SH) at three different levels. With the aid of the intelligent and distributed control, these decision-making levels can be interchanged in response to the variable situations. Such a mechanism provides the dynamic flexibility of heterarchy while preserving the stability of hierarchy.

3.3.5 New Management Style

Towards a holonic work organisation, Sun & Venuvinod (2001) suggested a new management style to supersede Taylor's management principles founded in the early twentieth century. Taylor (1911), as cited in Montgomery (1987), requested workers to just follow every order given by managers and superiors, namely "detailed instruction and supervision of each worker in the performance of that worker's discrete task". In a purely hierarchical and centralised manner, there is no delegation of authority, passing of important information, nor provision of wide-range training to workers. Such practice seems no reason for sustainable improvement and has become a critical factor to flexible organisations, thus requiring a paradigm shift in management style. On this account, the development of HWM intends to adopt the holonic control paradigm that accommodates the principles of decentralisation and hierarchy-heterarchy combination.

In HWM, the function blocks are able to exchange information and make negotiation under certain circumstances, owing to the four control attributes stated. The cross-training strategy integrated in this novel model does not follow any fixed pattern; and as at that, the cross-training chances given are varying from case to case, depending on the worker skill and the task urgency.

The new management style leading to the formation of HWM is outlined in Figure 6.

4. Experimental Setup and Results

A mock-up test record with twenty-four-month data analysis was created using Microsoft Excel®, in an attempt to study the effectiveness of WOZIP (Lim 2011a; Lim 2011b). The resultant datasheet and graph indicate that this pre-active planning method for HWM is able to respond to the trend of the varying machine utilisation and worker idling rates, upon the different levels of disturbance.

On the other hand, a case study was conducted on a local carton manufacturer, so as to verify the WOSEG (Lim 2011a; Lim & Chin 2011a). The processing time data were collected from five major tasks: laminate the structure, make the lid, make the legs, make the box, and assemble the final product. A computer simulation model was designed assuming a few scenarios to compare the WOSEG with some commonly used selection rules based on overdue rate, average skill level, interpersonal and intrapersonal skill deviations. In operational research, simulation is known as a powerful technique to model a real-life or hypothetical environment of dynamic and stochastic behaviour (Hlupic *et al.* 2006). For the input instruction coding and output analysis purposes, a software package inclusive of Witness®, Visual Basic®, and Microsoft Access® were used in the author's experimentation. The simulation results conclude that the WOSEG is superior to the others as it consistently achieves the lowest overdue rate and higher average skill level, with moderate workload balance and cross-training tendency. Such a reactive selection guide under the HWM is capable of balancing the requirements to meet delivery time limit via specialisation and to improve workforce flexibility via cross-training. More importantly, the minimal overdue rate reflects that the aggregate impact of absenteeism and turnover can be substantially diminished, thus fulfilling the author's research aims.

5. Conclusion

In order to complete the series of HWM research papers (Lim *et al.* 2008; Lim & Chin 2008; Lim 2011a; Lim 2011b; Lim & Chin 2011a; Lim & Chin 2011b), the combination of WOZIP and WOSEG is elaborated in this journal article, with an emphasis on holonic control measures and strengths.

The WOZIP, on the quantitative and pre-active side of HWM, plans the number of workers to serve on a production floor in a certain period of time. This helps to avoid excess of labour supply as well as impairment due to absenteeism and turnover. The rates of machine utilisation, workforce disturbance and idleness acquired from the previous period are essential for this purpose and so they are forecasted using exponential smoothing for the coming period.

The WOSEG, as the qualitative and reactive part of HWM, is able to determine which worker to handle which task, with an intention to promote the workforce flexibility through giving cross-training opportunities, while exerting minimum pressure on the overall productivity. During the selection process, the worker availability and skill and the task urgency have to be taken into consideration.

In future, a costing framework may be devised and attached to both WOZIP and WOSEG, whereby the aggregate of fixed and variable costs in production, along with the individual cost of each functioning unit, can be estimated and minimised.

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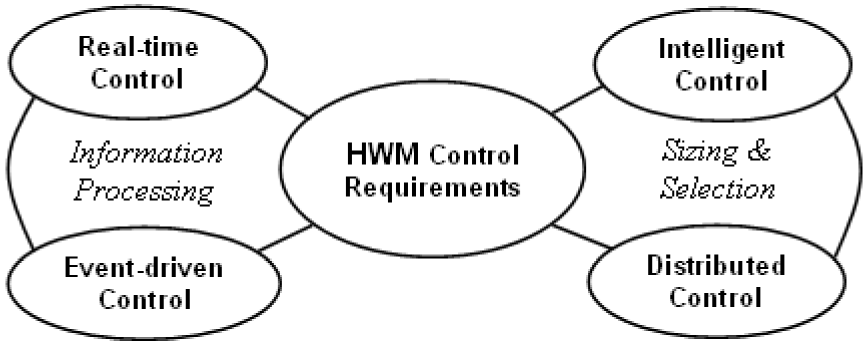

Figure 1. Control Requirements of HWM

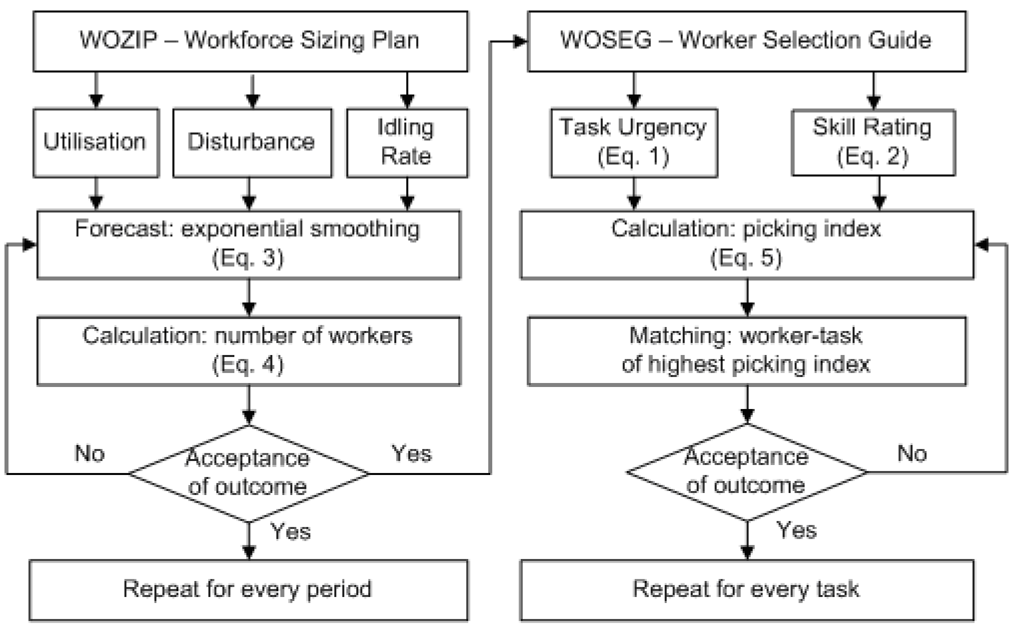

Figure 2. Block Diagram of HWM

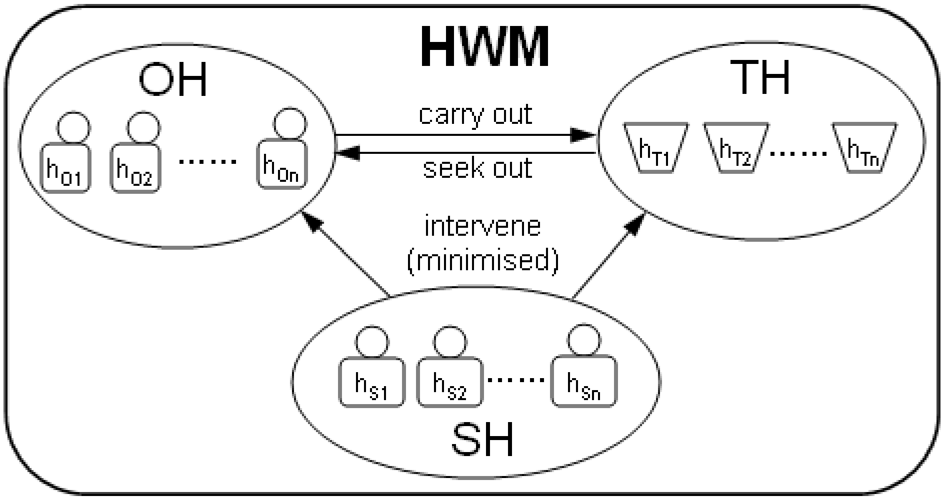

Figure 3. Holons and sub-holons in HWM

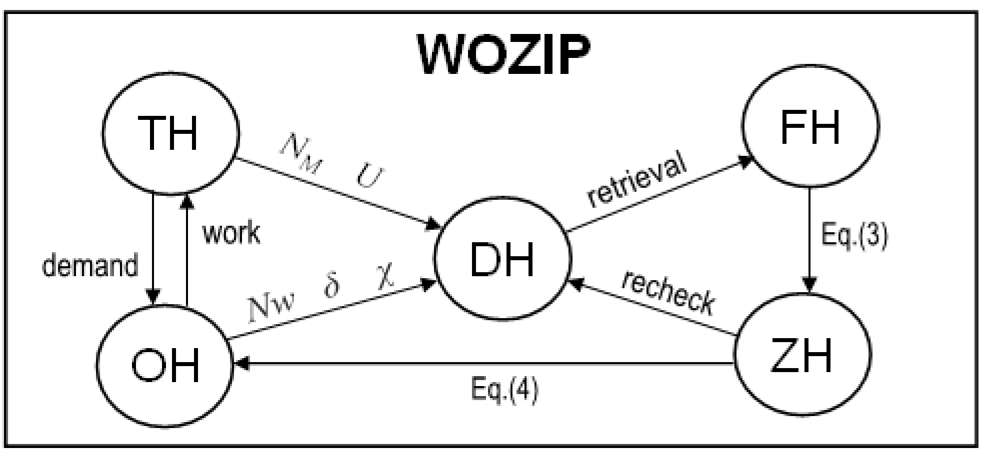

Figure 4. Holarchy of WOZIP

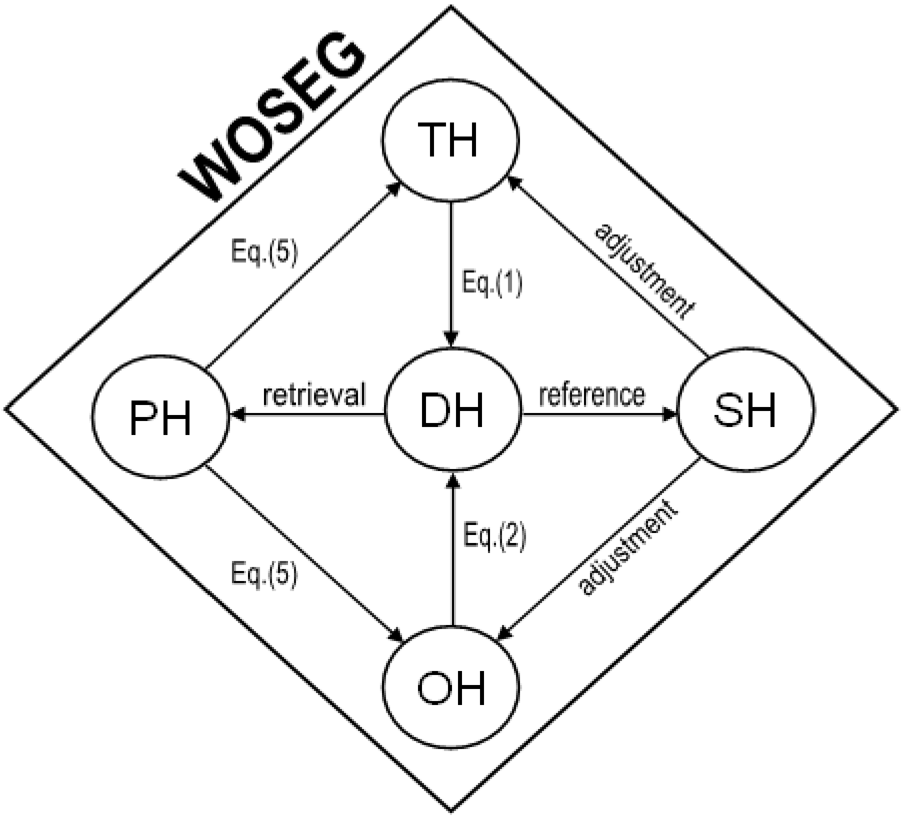

Figure 5. Holarchy of WOSEG

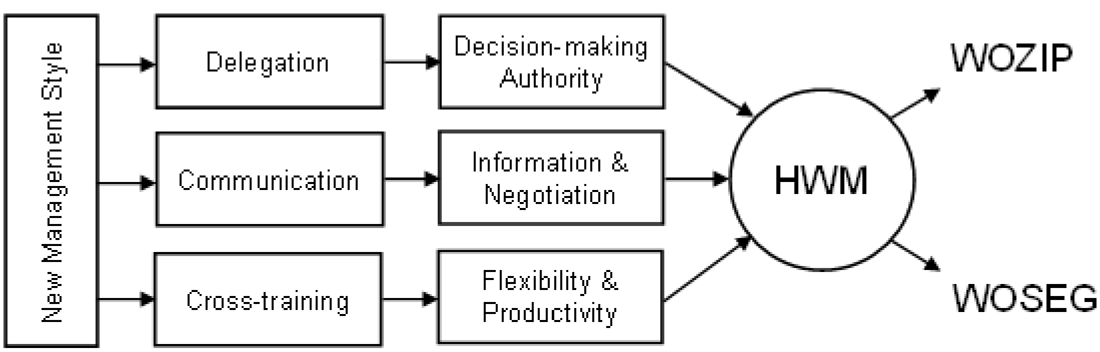

Figure 6. New Management Style