A hormone regulation-based approach for distributed and on-line scheduling of machines and AGVs

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Abstract

With the continuous innovation of technology, automated guided vehicles (AGVs) are playing an increasingly important role on manufacturing systems. Both the scheduling of operations on machines as well as the scheduling of AGVs are essential factors contributing to the efficiency of the overall manufacturing systems. In this paper, a hormone regulation based approach for online scheduling of machines and AGVs within a distributed system is proposed. In a real-time environment, the proposed approach assigns emergent tasks and generates feasible schedules implementing a task allocation approach based on hormonal regulation mechanism. This approach is tested on two scheduling problems in literatures. The results from the evaluation show that the proposed approach improves the scheduling quality compared with state-of-the-art on-line and off-line approaches.

Keywords:

Manufacturing system; Automated guided vehicle (AGV); Hormone-regulation mechanism; On-line scheduling; Allocation mechanism.

1. Introduction

With the globalization of markets, the continuous innovation of technology, and the short life of products, the traditional manufacturing industry is facing tremendous challenges. This situation has promoted the development of manufacturing systems towards the direction of discretization, intelligentization and autonomy. A manufacturing system typically consists of several production operation units, an automated storage/retrieval system (AS/RS) for raw material and finished products, and an automated material handling system for material transfer between units. In order to assure the high agility and flexibility, manufacturing systems require an intelligent and automated material handling system [1]. An automated guided vehicle system (AGVS) is one of the most efficient material handling systems due to high flexibility, safety and small space utilization of automated guided vehicles (AGVs). In recent years, the research on AGV technology has strengthened their flexibility, intelligence and autonomy [2-5].

An AGVS should ensure normal and efficient material transfer, meanwhile, reducing the transportation cost, work-in-process (WIP) inventories and total operation cost [5, 6]. To achieve these goals, many approaches and solutions are used in manufacturing systems. In these systems, scheduling problems are optimization processes of resource and task allocation. Both the scheduling of operations on machines as well as the scheduling of AGVs are essential factors contributing to the efficiency of the manufacturing systems [7]. AGV scheduling problems depend on the machine scheduling for task execution, specifically on the starting and ending time assigned by the operations' scheduling. The objective of AGV scheduling is to optimize the material handling, executed by AGVs, among the machines and the AS/RS. AGV scheduling can be achieved by both off-line and on-line approaches. Off-line scheduling is aimed to manage all activities for the entire scheduling period; while, on-line scheduling carries out the allocation and dispatching in real-time, during the execution of the plan.

Off-line AGV scheduling is a NP-hard problem that must take into account machine scheduling and AGV scheduling simultaneously. Numerous research results show that NP-hard scheduling problems can be solved by heuristic approaches [8-10], as well as off-line AGV scheduling problem [11]. In order to optimise AGV scheduling, Confessore et al. [12] propose a network based heuristic approach for the vehicle dispatching. Bilge and Ulusoy [13] exploit the interactions between machine scheduling and AGV scheduling in a flexible manufacturing system (FMS) by addressing them at the same time. They define a nonlinear mixed integer-programming model to formulate the problem. They apply a heuristic-based iterative approach to generate machine schedules that are used to define time windows for AGVs; afterwards a feasible solution for AGV schedules is searched. Besides, several more researches [14-17] solve scheduling problems in the literature [13] by using meta-heuristic techniques.

The goal of off-line scheduling is to generate an optimized schedule over a period of time, during which the schedule is not expected to require any change. Nevertheless, during production, disturbances are likely to cause the unavailability of the original schedule. Therefore, on-line scheduling or dispatching approaches can substantially improve the performance of AGVSs [18-20]. There are two on-line approaches for AGVSs: centralized and decentralized (or distributed). A centralized approach has one controller for all AGVs in the system [21-23].

Whereas, in a distributed approach there are several subsystems controlled by different independent controllers based on their local knowledge. Multi-Agent Systems (MASs) and Holonic Manufacturing System (HMS), with distributed characteristic, can be used to implement on-line AGV routing and dispatching. Lau and Woo [24] describe an agent-based dynamic routing strategy for generic automated material handling systems. Morten and Olivier [25] present a holonic based approach for AGVS developed for the automated paint-shop. Babiceanu et al. [26] introduce a holonic control approach for scheduling material handling devices in the cellular manufacturing environment. There are also some researchers applying distributed approaches to deal with classic objectives existing for AGV routing and dispatching, such as deadlock, conflict, etc. Singh and Tiwari [27] propose a MAS approach for the operational control on AGV conflict-free routing. Breton et al. [28] introduce a routing approach based on MAS for deadlock avoidance and conflict free. Wallace [29] presents an agent-based AGV controller to maintain deadlock-free flow of AGVs within a free space world model.

Although there have been many researches on on-line AGV routing and dispatching by applying distributed approaches, very few carry out the study on on-line scheduling for machines and AGVs simultaneously. To the best of the authors' knowledge, only one work [30] proposes a MAS approach for simultaneous scheduling of machines and AGVs. The approach works in an on-line environment and generates feasible schedules using negotiation and bidding mechanisms between distributed agents. MAS negotiation and biding mechanisms have the advantage of simplicity. Nevertheless, since they are a type of explicit coordination mechanism, when the complexity of the manufacturing environment increases (the number of machines and AGVs is large, together with a high number of new tasks appearing at run time), the number of messages passing is also large, and time consumption in some situations is not appropriate for given feasible solutions in due date [31, 32].

Intelligent models inspired by human body information processing mechanism have become a new research focus in the Artificial Intelligence research field. For example, endocrine system is a core part of human body information processing mechanism. Its unique processing method, based on the principle of hormone diffusion and reaction, has given researchers a lot of inspiration [33, 34]. The hormone-regulation mechanism is one kind of implicit coordination approach that leads to quick coordination between the different components of the entire system. Compared with MAS negotiation and bidding mechanisms, this mechanism implements simpler coordination and requires less message passing among the system components. In this work, an approach for distributed and on-line scheduling of AGVs and machines that uses the hormone-regulation mechanism is proposed.

The remainder of the paper is organized as follows. Section 2 presents an on-line scheduling model inspired by the principle of hormone diffusion and reaction to agilely deal with emergent tasks. Section 3 introduces a transportation task allocation mechanism based on hormone-regulation mechanism. Section 4 illustrates a hormone regulation based cooperation mechanism between machines and AGVs for on-line scheduling. Section 5 presents an evaluation study in which the proposed approach is compared against other state-of-the-art approaches. Section 6 describes the conclusions and future works.

2. On-line scheduling model

2.1. On-line scheduling approach

An on-line problem for simultaneous scheduling of machines and AGVs can be modelled as an on-line job shop scheduling problem in which the materials are transported by AGVs. The process route plan generated from an on-line job shop scheduling determines the key time nodes of an on-line AGV scheduling. In recent years, on-line job shop scheduling problems for manufacturing systems have been studied by many researchers [35-37]. In our previous work [38], a shop floor re-scheduling approach was presented. This technique can deal with on-line scheduling for machines and operations proposed in this article. Thus, the focus of this paper is the scheduling of transportation tasks between AGVs and machines, shown in Figure 1.

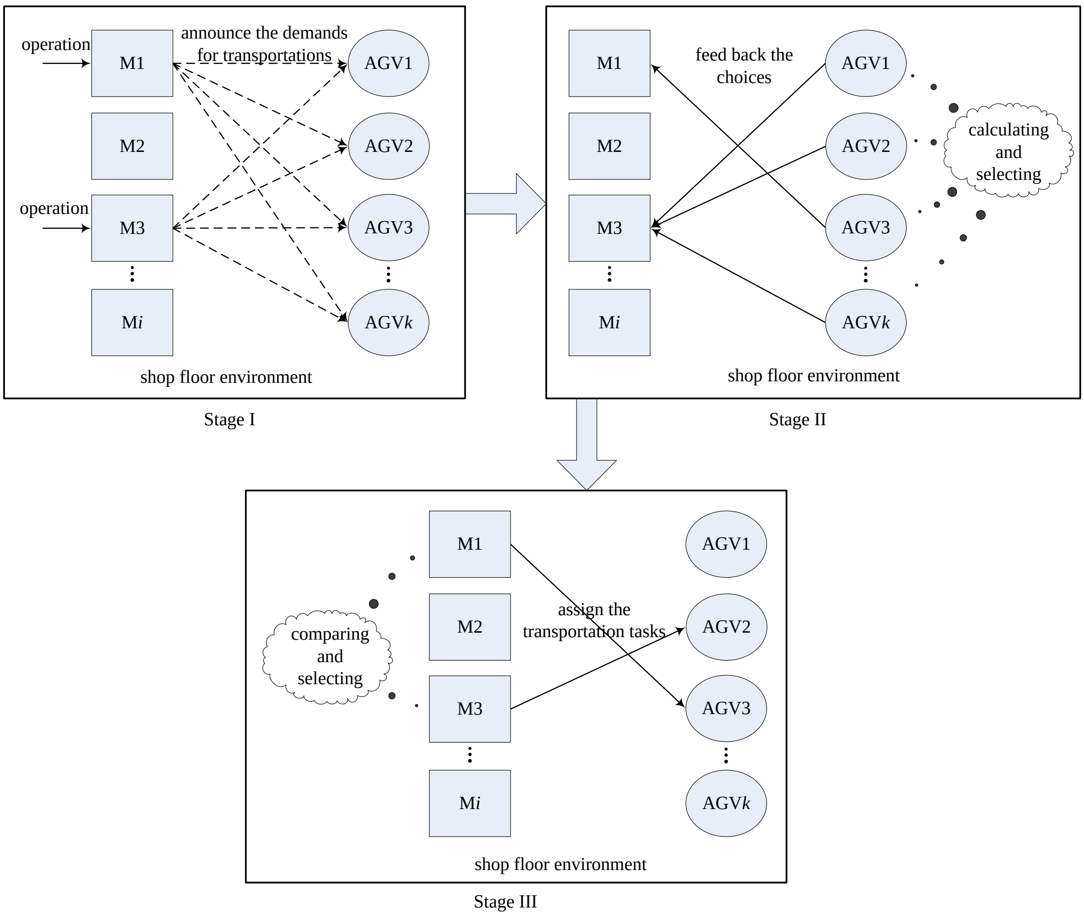

Figure 1. Scheduling of transportation tasks between AGVs and machines

This scheduling approach is collaborative and distributed, and can be described in an abstract way as follows. The collaborative scheduling process is divided into three stages. In stage I, the scheduling process is triggered when an operation is started on a machine; the machine must deal with the subsequent transportation throughout the shop floor before the operation is finished. The machine needs to find a suitable AGV that can execute the transportation. To this end, it sends the demand requirement to the AGVs in the system. In stage II, when a given AGV realizes the demands from machines (sensing the environment or receiving a message), calculates its transportation efficiency for every demand and selects the demand with the highest transportation efficiency according to its own criteria, then communicates its choice back to the relevant machine. In stage III, the machine receives/senses the feedback information, then evaluates the different alternatives and selects the most efficient one. Finally, the machine allocates the transportation task to the selected AGV. In the next subsections, an on-line scheduling model inspired by the principle of hormone diffusion and reaction is detailed.

2.2. Information processing mechanism in endocrine system

The endocrine system of the human body is a complex physiology network formed by a variety of endocrine glands. These endocrine glands can influence each other by secreting, transmitting and responding to different hormones [39]. Endocrine glands with different functions have their own proprietary hormone receptors, which react to hormones in the humoral environment. However, endocrine glands diffuse hormones into the humoral environment with no constraints; the hormone receptors only respond to the specific hormones. The principle of hormone diffusion and reaction in the endocrine system is illustrated in Figure 2. The solid lines with an arrow represent the hormone secretion between endocrine glands or hormone autocrine in independent endocrine glands; whereas the dotted line with an arrow indicates the hormone feedback of endocrine glands from the participant to the initiator. For example, affected by a stimulus, endocrine gland "A" secretes hormone "A" and releases it into the humoral environment. Sensing the stimulus from hormone "A", endocrine gland "B" secretes hormone "AB" and autocrine hormone "B" simultaneously. Then endocrine gland "B" feeds back hormones "AB" and "B" to endocrine gland "A".

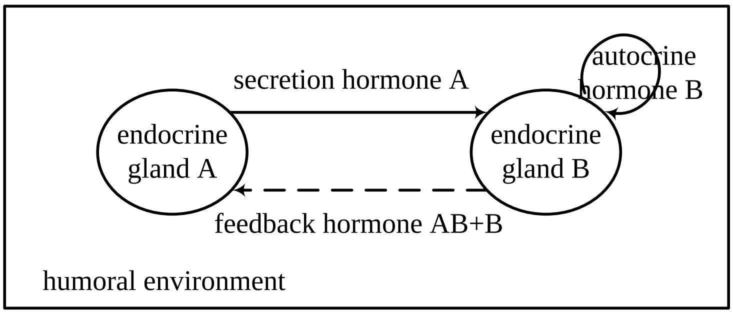

Figure 2. Principle of hormone diffusion and reaction in endocrine system

The principle of hormone diffusion and reaction in endocrine system is provided with the following characteristics:

(1) Information transmission functions. There is no centralized control part, but only one humoral environment for hormone transmission. Moreover, the behaviours of hormone secretion in endocrine glands are only related to the hormone information in the humoral environment. Thus it is not required a point-to-point communication.

(2) Specificity. A hormone is a kind of chemical component released by endocrine glands. The combination of the chemical component and hormone receptors is specific, i.e. a hormone receptor only reacts to a specific chemical component (hormone). The specificity of hormone is determined by the genetic information.

(3) Synergy and antagonism between hormones. In the endocrine system, endocrine glands release hormones through stimulus in the humoral environment, where synergy and antagonism between hormones emerge from the different effects of hormones on the same gland. These kinds of interactions have the effect to stabilize the system environment.

By employing the features of hormone transmission and interaction, the endocrine system of the human body can achieve rapid adjustment and maintain high adaptability.

2.3 On-line scheduling model inspired by the principle of hormone diffusion and reaction

To solve the on-line scheduling problem, an on-line scheduling model inspired by the principle of hormone diffusion and reaction is proposed (Figure 3). Acting as endocrine glands, the machines play the role of initiators providing optimization and coordination services to AGVs, and AGVs play the role of participants providing response and optimization services. In our model, it is assumed that machines and AGVs have the capacity to handle calculation, comparison, and decision-making operations, since the computation power and the optimization capability are embedded in them. In the proposed model, the tasks act as the stimulus in the system; the shop floor environment acts as the humoral environment. In this way, the diffusion and reaction information are similar to the secretion and feedback of hormones.

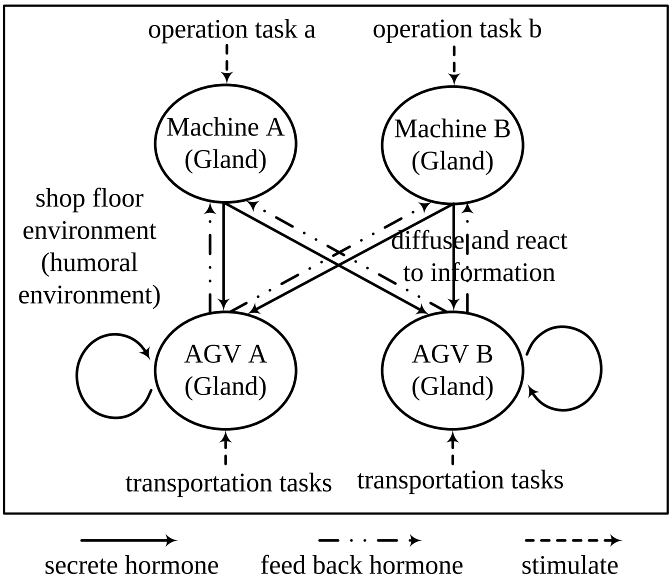

Figure 3. On-line scheduling model inspired by the principle of hormone diffusion and reaction

As illustrated in Figure 3, when operation task “a” is executed on machine “A”, the subsequent need for transportation task “a” emerges. Stimulated by that need, machine “A” evaluates the degree of demand for AGVs; then it packages the demand and transportation task information into a hormone; and finally diffuses the hormone into the shop floor environment. When the AGVs sense the hormone information, they are stimulated by the demand and the transportation task simultaneously. In response to the stimulus, each AGV evaluates how the demand influences itself, and its performance to complete the transportation task; then it packages the evaluated value into relevant hormone information and releases this information to machine “A”. According to the feedback hormone information, machine “A” allocates the transportation task to the relevant AGV. In the process of on-line scheduling, the information evaluation of machines and AGVs is similar to the process of responding to stimulus and secreting hormone, which is a kind of self-adjustment and adaptation mechanism to maintain the balance of the system. By utilizing this model, the transportation tasks can be rapidly allocated without a supervisor. In the next section, the allocation process of transportation tasks is described in detail.

3. Allocation mechanism based on hormone-regulation mechanism

3.1. Hormone-regulation mechanism background

Farhy [40] defined the basic law for modelling the secretion of hormones by endocrine glands. In this model, the hormone regulation complies with *Hill* function which is composed of the rising function $F_{up}(C)$ and decreasing function $F_{down}(C)$, shown in Eq. (1).

$$F(C)=\begin{cases} F_{\text{up}}(C)=\dfrac{C^n}{T^n+C^n}, & \text{rising function} \\ F_{\text{down}}(C)=\dfrac{T^n}{T^n+C^n}, & \text{decreasing function} \end{cases} \quad (1),$$

where C is variable of hormone concentration; T is a threshold of hormone concentration and $T>0$; n is the *Hill* coefficient and $n>1$

If a hormone x is controlled by a set of hormones $I=\{1, 2,\ldots,i\}$ simultaneously, the secretion speed of hormone x is determined by the concentration of these hormones, which is shown in Eq. (2).

$$S_x = S_{x0} + \sum_{i=1}^{I} a_i \cdot F(C_i) \quad (2),$$

where S_{x0} represents the initial secretion speed of hormone x, C_i is the concentration of hormone i, and coefficient a_i is a positive constant associated with hormone i.

For example, the glucagon secreted by pancreatic islet α-cells has the function of raising blood sugar concentration; on the contrary, the insulin secreted by pancreatic islet β-cells has the function of reducing blood sugar concentration. When the blood sugar concentration is low, islet α-cells promote the glucagon secretion, and hormone regulation complies with up-*Hill* function for rapidly improving the blood sugar concentration; on the contrary, when the blood sugar concentration is high, islet *β*-cells promote the insulin secretion, and hormone regulation complies with down-*Hill* function for agilely reducing the blood-sugar concentration. Because hormone regulation has the characteristics of monotonicity and non-negativity, the affection of one hormone to another hormone can only be the stimulation or inhabitation. In biology, insulin and glucagon exist at the same time, and have the function of mutual antagonism to regulate blood sugar concentration.

If S_x represents the secretion speed of blood sugar, and C_y and C_z are the hormone concentration of insulin and glucagon respectively, S_x can be calculated according to the influence on blood sugar concentration caused by antagonism between glucagon and insulin.

$$S_x = S_{x0} + a_y F_{\mathrm{up}}(C_y) + a_z F_{\mathrm{down}}(C_z) \qquad (3).$$

There are not only antagonistic effects but also synergistic effects between different hormones. For example, glucagon and epinephrine have the synergistic function of elevating blood sugar concentration. If S_x represents the secretion speed of blood sugar, and C_y and C_z are the hormone concentration of glucagon and epinephrine respectively, S_x can be calculated in accordance with the influence on blood sugar concentration caused by synergy between glucagon and epinephrine.

$$S_x = S_{x0} + a_y F_{\mathrm{up}}(C_y) + a_z F_{\mathrm{up}}(C_z) \qquad (4).$$

The next sections describe the design of AGV allocation approach inspired by hormone-regulation mechanism.

3.2. Time parameters in scheduling

In the on-line scheduling problem of machines and AGVs, a task has two main stages: the task being operated by a machine (*TO*) and the task being transported by an AGV (*TT*), shown in

Figure 4. The notations are given below:

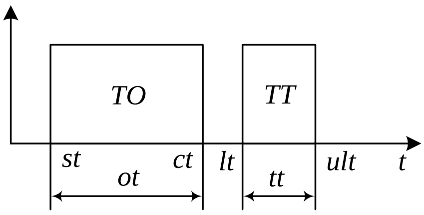

Figure 4. Two main stages of a task

st is the start time of an operation task.

ct is the completion time of an operation task.

ot is the duration of an operation task.

lt is the loading time of a transportation task.

ult is the unloading time of a transportation task.

tt is the duration of a transportation task.

M is the set of machines.

K is the set of AGVs.

J is the set of jobs.

L is the set of operations of a job.

Z is the makespan.

The objective of on-line scheduling problem of machines and AGVs is to minimize *Z*. According to the interrelation between time parameters, constraints are extracted and formulized as follows:

$$st_{jl+1} \geq ct_{jl} + tt_{jl}, j \in J, l \in L \quad (5);$$

$$ct_{jl} + tt_{jl} \leq ult_{jl} \leq st_{jl+1}, j \in J, l \in L \quad (6).$$

Formula (5) presents a time constraint between adjacent operations of a job; and Formula (6) presents time constraints between AGV and adjacent operations of a job. In the on-line scheduling problem, only *ot* and *tt* are considered as given parameters, and other parameters are variables to be determined. According to the constraints (5) and (6), interrelation between parameters are determined. Taking the operation *l* of job *j* as an example, calculation processes of the above parameters are illustrated as follows.

When an operation task (TO_{jl}) is executed on a machine, st_{jl} and ot_{jl} are determined. And then ct_{jl} can be obtained in accordance with Eq. (7).

$$ct_{jl} = st_{jl} + ot_{jl} \qquad (7).$$

According to the operation state of AGV (i.e. transporting a task; or being idle and waiting for a task to transport), the loading time of AGV is described by the following equations:

$$lt_k^{jl} = \begin{cases} \begin{cases} eft_k^{jl} + \Delta t(NL, PL_{jl}), & eft_k > ept_{jl} \\ eft_k^{jl} + \max\{\Delta t(NL, PL_{jl}), (ept_{jl} - eft_k)\}, & eft_k \le ept_{jl} \end{cases} & \text{transporting state} \\ \begin{cases} t + \Delta t(CL, PL_{jl}), & t > ept_{jl} \\ t + \max\{\Delta t(CL, PL_{jl}), (ept_{jl} - t)\}, & t \le ept_{jl} \end{cases} & \text{idle or waiting state} \end{cases} \qquad (8),$$

where *t* is the current time; eft_k is the earliest finish time of the current transportation task of AGV_k; ept_{jl} is the earliest pickup time of the operation *l* of job *j*; *NL* and *CL* denote the next location and current location of AGV_k respectively; PL_{jl} is the pickup location of the operation *l* of job *j*; and Δt is the required transportation time between two locations. In this paper, the post-processes after TO_{jl} are not taken into account, therefore, the value of ept_{jl} is equal to ct_{jl} ($ept_{jl} = ct_{jl}$). The upper part of Eq.(8) defines the situation in which the AGV is transporting a task; and the lower part of Eq.(8) defines the situation in which the AGV is idle and waiting to transport a new task.

When the workpiece is picked up by AGV_k, tt_{jl} is calculated as follows:

$$tt_{jl} = \Delta t(PL_{jl}, DL_{jl}) \qquad (9),$$

where DL_{jl} is the destination location of the operation l of job j.

The unloading time of AGV_k is computed according to Eq. (10).

$$ult_{jl} = lt_k^{jl} + tt_{jl} \quad (10).$$

Finally, the makespan is selected in accordance with Eq. (11)

$$Z = \mathrm{MAX}_{j \in J}\{ult_{jL_j}\} \quad (11),$$

where L_j is the number of the last operation of job j.

3.3 Allocation mechanism

In the case of normal operation, hormone concentrations of the multi-AGV system are in the equilibrium state. Once a transportation task emerges in the manufacturing system, the balance will be disturbed. It is assumed that the secretion of hormone is triggered in the manufacturing environment, stimulated by the transportation task. The level of hormone concentration is related to the effect on the system balance caused by the initiation of transportation task. If the effect on the system balance is small, the level of hormone concentration released by the system is low; otherwise, the level of hormone concentration is high. Taking this principle as a basis, a transportation task allocation mechanism is proposed. In the following subsections, the operation l of job j is taken as an example to describe the allocation mechanism in detail.

3.3.1 Hormone secretion of machines

When an operation task (TO_{jl}) is executed on one machine (M_m), the allocation of transportation task (TT_{jl}) will be triggered; at the same time, M_m will search for the appropriate AGV to perform TT_{jl}. In order to ensure that TT_{jl} can be started after ct_{jl}, which means the workpiece of TT_{jl} is picked up by an AGV at time ct_{jl}, TT_{jl} stimulates M_m to secrete hormone according to Eq. (15). The level of hormone concentration represents the urgency of the machine's demand for an AGV.

$$H_m^{jl}(t) = ce^{(t-ct_{jl})/ot_{jl}} \quad (12),$$

where, *c is a positive constant.*

An example of hormone secretion curve of a machine is shown in Figure 5 according to Eq. (12). When $t < ct_{jl}$, $H_m^{jl}(t) < c$ can be obtained, and the hormone concentration increases moderately as time goes on. It indicates that there is a less demand for an AGV to perform TT_{jl}. When $t \geq ct_{jl}$, $H_m^{jl}(t) \geq c$ can also be obtained, and the hormone concentration increases faster with the passage of time. It demonstrates that the demand for an AGV to perform TT_{jl} is urgent.

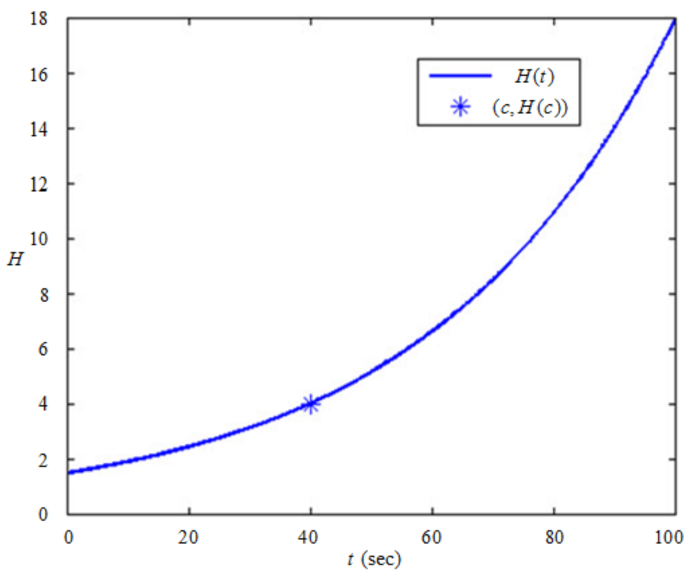

Figure 5. Hormone secretion curve of machine stimulated by transportation task

3.3.2 Hormone secretion of AGVs

When an AGV with transport capability senses the stimulation of $H_m^{jl}(t)$, the AGV will secrete hormone according to the secretion speed proposed in Eq. (13).

$$S_k(H_m^{jl}(t)) = \begin{cases} S_k^{basal} + a_H F_{\text{down}}(H_m^{jl}(t)), H_m^{jl}(t) < c \\ S_k^{basal} + a_H F'_{\text{down}}(H_m^{jl}(t)), H_m^{jl}(t) \geq c \end{cases} \quad (13),$$

where, S_k^{basal} is the basal secretion speed of AGV$_k$ and $S_k^{basal} \geq 0$.

An example of hormone secretion speed curve of AGV stimulated by $H_m^{jl}(t)$ (Figure 6) is plotted in accordance with Eq.(13). Affected by the inhibition of $H_m^{jl}(t)$, the secretion speed of AGV$_k$ reduces as time goes on. When $t \geq ct_{jl}$, $H_m^{jl}(t)$ will speed up to inhibit the hormone secretion of AGV$_k$, to assure that the machine with higher hormone concentration ($H_m^{jl}(t)$) can be selected more easily.

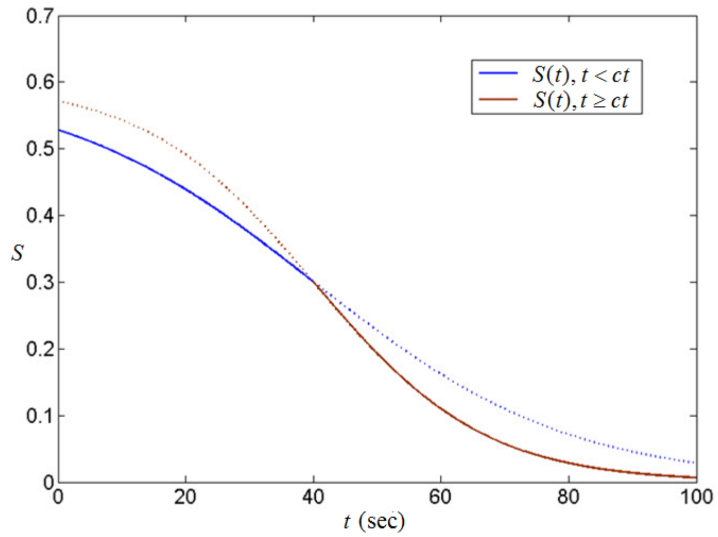

Figure 6. Hormone secretion speed curve of AGV stimulated by $H_m^{jl}(t)$

Besides $H_m^{jl}(t)$, TT_{jl} can also stimulate AGV$_k$ to secrete hormone. In such case, stimulated by TT_{jl}, AGV$_k$ computes the time node (ult_{jl}) to complete TT_{jl} according to Eq.(10). The performance of AGV$_k$ to finish TT_{jl} depends on the time interval between ult_{jl} and st'_{jl+1}, where st'_{jl+1} is the earliest and estimated start time of the next operation of job j under the constraints. Thus, stimulated by the performance of an AGV to finish a transportation task, the AGV secretes hormone in accordance with Eq. (2) as follow:

$$S_k(ult_{jl}) = \begin{cases} S_k^{basal} + a_{ult} F_{\text{down}}(ult_{jl}), ult_{jl} < st'_{jl+1} \\ S_k^{basal} + a_{ult} F_{\text{up}}(ult_{jl}), ult_{jl} \geq st'_{jl+1} \end{cases} \quad (14).$$

When $ult_{jl} < st'_{jl+1}$, the hormone secretion of AGV$_k$ complies with the down-*Hill* function, otherwise complies with the up-*Hill* function.

An example of hormone secretion speed curve of AGV stimulated by *ult* (Figure 7) is plotted according to Eq.(14). When ult_{jl} is close to st'_{jl+1}, the secretion speed is slower. It indicates that AGV$_k$ can be a better option to complete TT_{jl}, thus it is easier for AGV$_k$ to be selected; on the contrary, when ult_{jl} is far from st'_{jl+1}, the secretion speed is faster. It indicates that AGV$_k$ can be a worse option to complete TT_{jl}, thus it is more difficult for AGV$_k$ to be selected.

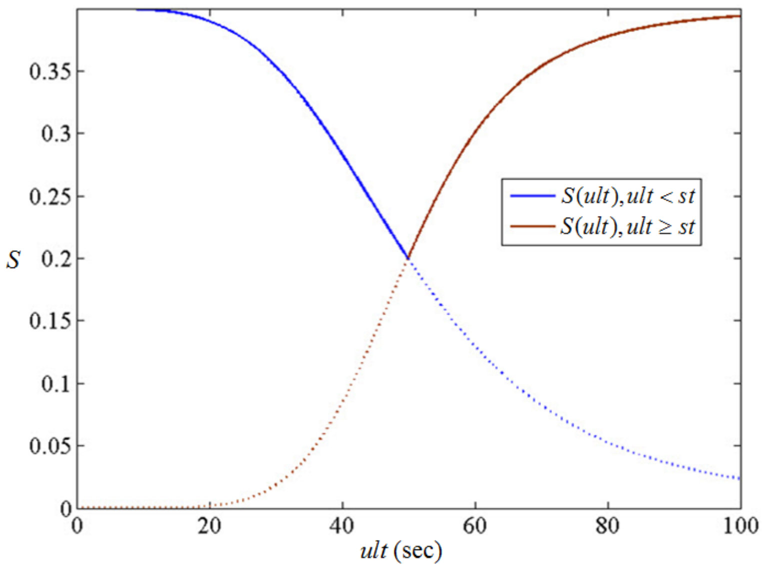

Figure 7 Hormone secretion speed curve of AGV stimulated by *ult*

As mentioned above, the hormone secretion of AGV$_k$ is simultaneously influenced by two independent hormones ($H_m^{jl}(t)$ and ult_{jl}). Thus stimulated by both $H_m^{jl}(t)$ and ult_{jl} at the same time, AGV$_k$ secretes hormone in accordance with the speed following Eq.15.

$$S_k(H_m^{jl}(t), ult_{jl}) = \begin{cases} a_H F_{\text{down}}(H_m^{jl}(t)) + a_{ult} F_{\text{down}}(ult_{jl}) + S_k^{basal}, t < ct_{jl}, ult_{jl} < st'_{jl+1} \\ a_H F_{\text{down}}(H_m^{jl}(t)) + a_{ult} F_{\text{up}}(ult_{jl}) + S_k^{basal}, t < ct_{jl}, ult_{jl} \geq st'_{jl+1} \\ a_H F'_{\text{down}}(H_m^{jl}(t)) + a_{ult} F_{\text{down}}(ult_{jl}) + S_k^{basal}, t \geq ct_{jl}, ult_{jl} < st'_{jl+1} \\ a_H F'_{\text{down}}(H_m^{jl}(t)) + a_{ult} F_{\text{up}}(ult_{jl}) + S_k^{basal}, t \geq ct_{jl}, ult_{jl} \geq st'_{jl+1} \end{cases} \quad (15).$$

3.3.2 Decision making

When a machine senses the set $\{S_k(H_m^{jl}(t), ult_{jl})\}$, it will allocate TT_{jl} to an AGV with the minimum secretion speed of hormone at time *t* according to Eq.(16).

$$S_k(t) = \min_{k \in K}\{S_k(H_m^{jl}(t), ult_{jl})\} \quad (16).$$

A machine selects the right (i.e. optimal) AGV according to the secretion speed of hormone, in which a machine's need for an AGV and the performance of an AGV to perform a transportation task are taken into account simultaneously. In the selection of a transportation task, a weighted loading time is proposed as follow:

$$l\tilde{t}_k^{jl} = (lt_k^{jl} - t) / H_m^{jl}(t) \quad (17).$$

The weighted loading time reflects transportation efficiency between different tasks considered the influence of hormone $H_m^{jl}(t)$. When an AGV senses the set $\{H_m^{jl}(t), TT_{jl}\}$ from different machines, it will select the transportation task with the minimum weighted loading time in accordance with Eq.(18).

$$lt_k' = \min_{j \in J, l \in L}\{l\tilde{t}_k^{jl}\} \quad (18).$$

Therefore, stimulated by multiple tasks to transport, an AGV will choose the task with the highest transportation efficiency to secrete hormone. Taking transportation tasks as the communication media of mutual selection between AGVs and machines, the arrival of tasks on time and the transportation efficiency of the AGV system can be ensured simultaneously. In the processes of optimization, AGV can select the next task to transport ahead of schedule, so the coherence of processing between previous and the next operations can be guaranteed.

4. Distributed cooperation mechanism for on-line scheduling

In this section, a distributed cooperation mechanism for on-line scheduling is elaborated. This mechanism is mainly to solve mutual selection and optimization between machines and AGVs. The goal of the mechanism is that the distributed system can achieve an optimized production status and maintain a high production level. As shown in Figure 8, machines and AGVs are considered autonomous and cooperative cells [41] that follow the steps given below to conduct their inherent operations:

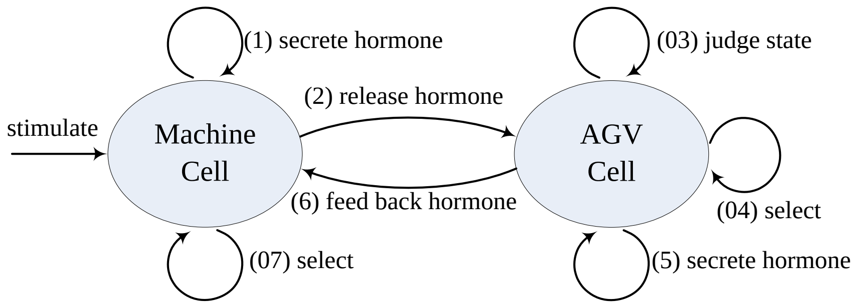

Figure 8 Distributed Cooperation mechanism between machines and AGVs

Step (1) When an operation task (TO_{jl}) is performed on one machine (M_m) at current time (t), the subsequent transportation task (TT_{jl}) will be allocated to an AGV by machine cell m. Stimulated by TT_{jl}, machine cell m secretes hormone ($H_m^{jl}(t)$) according to the deviation between the completion time (ct_{jl}) and t.

Step (2) Machine cell m releases hormone information ($H_m^{jl}(t), TT_{jl}$) into the shop floor environment.

Step (3) When AGV cell k senses the set $\{H_m^{jl}(t), TT_{jl}\}$, it will check its transportation capacity. If number of transportation task is "0" or "1", it means that AGV_k is available for transportation; otherwise, AGV cell k feeds back the maximum hormones to the related machine cells, and goes to Step (6).

Step (4) AGV cell k extracts the required information from the set $\{H_m^{jl}(t), TT_{jl}\}$, and computes the weighted loading time set $\{l\tilde{t}_k^{jl}\}$ according to Eq.(17). Then, AGV cell k selects the transportation task with the highest efficiency (TT') in accordance with Eq.(18).

Step (5) Stimulated by $(H_m^{jl}(t), TT')$, AGV cell k calculates the hormone secretion speed $(S_k^{TT'}(t))$ according to Eq.(15).

Step (6) AGV cell k feeds back hormone information $(S_k^{TT'}(t))$ to the corresponding machine cell.

Step (7) When machine cell m senses the set $\{S_k(t)\}$ from different AGV cells, it awards TT_{jl} to the AGV with the minimum hormone secretion speed in accordance with Eq.(16).

Step (8) A loop between Step (1) to Step (7) is repeated until all the transportation tasks are allocated, then the makespan is selected according to Eq. (11).

Using this allocation mechanism, the machines can allocate the transportation tasks according to secretion speed of hormone, and the AGVs can select the transportation tasks with the premise of transportation efficiency. Finally, the objective of distributed and on-line scheduling of machines and AGVs can be achieved.

5. Experimental study

In order to simulate the proposed hormone regulation based approach for on-line scheduling, a series of instances were selected from the benchmarks of Bilge and Ulusoy [13]. These instances were used in both off-line and on-line scheduling by many researchers [11, 13-17, 30]. In this paper, the performance comparison between our proposal against off-line [16] and on-line [30] approaches of the specialized literature was carried out. In the experiments, the performance measure selected was makespan. The performance of the off-line approach is considered as the lower bound of on-line approaches. The constraints and assumptions of the experiments were in the following:

(1) One operation cannot be started before its preceding operations are finished and each machine is provided with sufficient input/output buffer space.

(2) The processing parameters of the operation tasks are deterministic such as operation time and setup time.

(3) All AGVs work with the same speed, and transport a single task at a time.

(4) Preemption is not allowed in transportation, i.e., once task transportation is started, it must be finished without interruption.

(5) Disturbances such as conflict, deadlock, delay, resource malfunction, etc. are not considered.

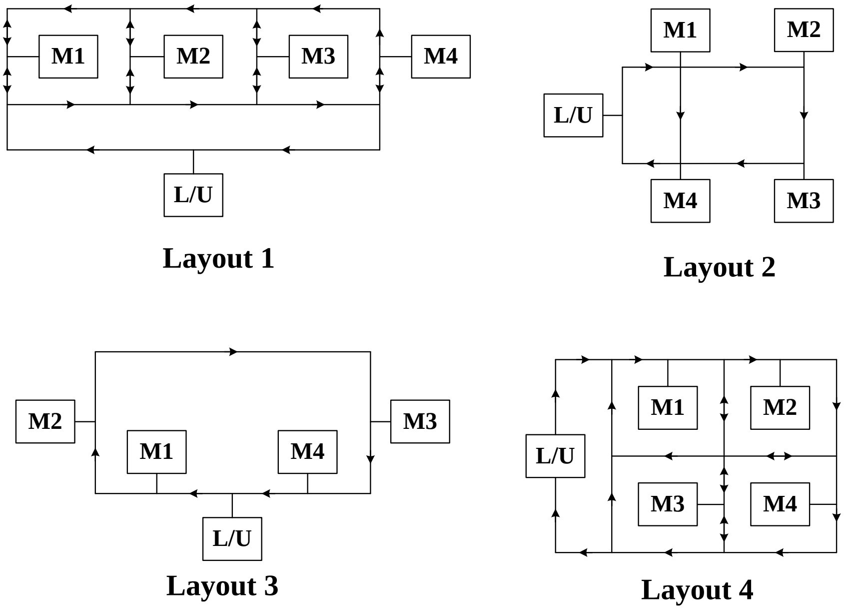

Figure 9. Layout schemes [13]

Let's assume an experimental scenario in which 2 AGVs travel between 4 machines and 1 load/unload (L/U) station. Figure 9 shows the layout schemes of the instances; Table 1 lists the transportation time matrix of AGV; and Table 2 gives the data sets of jobs. In the design of this test problem, the ratio between transportation time and operation time is taken into consideration as a significant characteristic. The ratio can be described as $\overline{tt}/\overline{pt}$, where $\overline{tt}$ represents the average value of the transportation time in the matrix, and $\overline{pt}$ indicates the average value of all the operation time in the job sets. According to the ratio ($\overline{tt}/\overline{pt}$), the problems can be divided into two groups: the one with relatively low ratio ($\overline{tt}/\overline{pt} < 0.25$) and the other with relatively high ratio ($\overline{tt}/\overline{pt} > 0.25$).

Table 1 Transportation time matrix of AGV [13]

	L/U	M1	M2	M3	M4
Layout 1					
L/U	0	6	8	10	12
M1	12	0	6	8	10
M2	10	6	0	6	8
M3	8	8	6	0	6
M4	6	10	8	6	0
Layout 2					
L/U	0	4	6	8	6
M1	6	0	2	4	2
M2	8	12	0	2	4
M3	6	10	12	0	2
M4	4	8	10	12	0
Layout 3					
L/U	0	2	4	10	12
M1	12	0	2	8	10
M2	10	12	0	6	8
M3	4	6	8	0	2
M4	2	4	6	12	0
Layout 4					
L/U	0	4	8	10	14
M1	18	0	4	6	10
M2	20	14	0	8	6
M3	12	8	6	0	6
M4	14	14	12	6	0

Table 2 Data sets of jobs [13]

JobSet1	JobSet2
Job1：M1(8); M2(16); M4(12);	Job1：M1(10); M4(18);

Job2：M1(20); M3(10); M2(18)	Job2：M2(10); M4(18)
Job3：M3(12); M4(8); M1(15)	Job3：M1(10); M3(20)
Job4：M4(14); M2(18)	Job4：M2(10); M3(15); M4(12)
Job5：M3(10); M1(15)	Job5：M1(10); M2(15); M4(12)
	Job6：M1(10); M2(15); M3(12)
JobSet3	JobSet4
Job1：M1(16); M3(15)	Job 1：M4(11); M1(10); M2(7)
Job2：M2(18); M4(15)	Job2：M3(12); M2(10); M4(8)
Job3：M1(20); M2(10)	Job3：M2(7); M3(10); M1(9); M3(8)
Job4：M3(15); M4(10)	Job4：M2(7); M4(8); M1(12); M2(6)
Job5：M1(8); M2(10); M3(15); M4(17)	Job5：M1(9); M2(7); M4(8); M2(10); M3(8)
Job6：M2(10); M3(15); M4(8); M1(15)	
JobSet5	JobSet6
Job1：M1(6); M2(16); M4(9)	Job1：M1(9); M2(11); M4(7)
Job2：M1(18); M3(6); M2(15)	Job2：M1(19); M2(20); M4(13)
Job3：M3(9); M4(3); M1(12)	Job3：M2(14); M3(20); M4(9)
Job4：M4(6); M2(15)	Job4：M2(14); M3(20); M4(9)
Job5：M3(3); M1(9)	Job5：M1(11); M3(16); M4(8)
	Job6：M1(10); M3(12); M4(10)
JobSet7	JobSet8
Job1：M1(6); M3(6)	Job1：M2(12); M3(21); M4(11)
Job2：M2(11); M4(9)	Job2：M2(12); M3(21); M4(11)
Job3：M2(9); M4(7)	Job3：M2(12); M3(21); M4(11)
Job4：M3(16); M4(7)	Job4：M2(12); M3(21); M4(11)
Job5：M1(9); M3(18)	Job5：M1(10); M2(14); M3(18); M4(9)
Job6：M2(13); M3(19); M4(6)	Job6：M1(10); M2(14); M3(18); M4(9)
Job7：M1(10); M2(9); M3(13)	
Job8：M1(11); M2(9); M4(8)	
JobSet9	JobSet10
Job1：M3(9); M1(12); M2(9); M4(6)	Job1：M1(11); M3(19); M2(16); M4(13)
Job2：M3(16); M2(11); M4(9)	Job2：M2(21); M3(16); M4(14)
Job3：M1(21); M2(18); M4(7)	Job3：M3(8); M2(10); M1(14); M4(9)
Job4：M2(20); M3(22); M4(11)	Job4：M2(13); M3(20); M4(10)
Job5：M3(14); M1(16); M2(13); M4(9)	Job5：M1(9); M3(16); M4(18)
	Job6：M2(19); M1(21); M3(11); M4(15)

All procedures were implemented in JAVA under JDK1.7.0 and the experimental tests were carried out on a 2.0 GHz Intel Core Duo computer with 2 GB Ram under Windows 7. Combining the 10 job sets and the 4 layout schemes from Tables 1 and 2, 82 test instances were created. These instances were tested using an off-line heuristic approach (HA) [16], a Multi-agent system approach (MAS) [30] and the proposed hormone regulation based approach (HRA). The off-line heuristic approach (HA) determined a lower bound of the makespan, so the aim of experimental study is to compare our proposal (HRA) against MAS and determine the deviation of both MAS and HRA with respect HA (Dev1, Dev2). Thus, we also shows the deviation of HRA with respect MAS (Dev3). The results for the case $\overline{tt}/\overline{pt} > 0.25$ are listed in Table 3, and for the case of $\overline{tt}/\overline{pt} < 0.25$ are shown in Table 4. The two numbers following EX represent the series of job set and the layout scheme. In table 4, a number "0" or "1" in the last position indicates that the operation times are doubled or tripled respectively, and in both cases transportation times are halved.

Table 3 Comparison results in the case of $\overline{tt}/\overline{pt} > 0.25$

		HA[16]	MAS[30]		HRA		
instance	$\overline{tt}/\overline{pt}$	makespan	makespan	Dev1%	makespan	Dev2%	Dev3%
EX11	0.59	**96**	130	35.42	122	27.08	-6.15
EX21	0.61	**100**	143	43.00	140	40.00	-2.10
EX31	0.59	**99**	142	43.43	148	49.49	4.23
EX41	0.91	**112**	198	76.79	174	55.36	-12.12
EX51	0.85	**87**	130	49.43	129	48.26	-0.77
EX61	0.78	**118**	153	29.66	153	29.66	0.00
EX71	0.78	**111**	129	16.22	146	31.53	13.18
EX81	0.58	**161**	196	21.74	199	23.60	1.53
EX91	0.61	**116**	178	53.45	147	26.72	-17.42
EX101	0.55	**147**	188	27.89	175	19.05	-6.91
EX12	0.47	**82**	98	19.51	100	21.95	2.04
EX22	0.49	**76**	86	13.16	86	13.16	0.00
EX32	0.47	**85**	114	34.12	114	34.12	0.00
EX42	0.73	**87**	129	48.28	120	37.93	-6.98
EX52	0.68	**69**	98	42.03	100	44.93	2.04
EX62	0.54	**98**	123	25.51	106	8.16	-13.82
EX72	0.62	**79**	92	16.46	101	27.85	9.78
EX82	0.46	**151**	172	13.91	156	3.31	-9.30
EX92	0.49	**102**	123	20.59	127	24.51	3.25
EX102	0.44	**135**	154	14.07	158	17.04	2.60
EX13	0.52	**84**	109	29.76	102	21.43	-6.42
EX23	0.54	**86**	98	13.95	96	11.63	-2.04
EX33	0.51	**86**	103	19.77	115	33.72	11.65

EX43	0.80	**89**	155	74.16	127	42.70	-18.06
EX53	0.74	**74**	109	47.30	113	52.70	3.67
EX63	0.54	**103**	128	24.27	110	6.80	-14.06
EX73	0.68	**83**	93	12.05	119	43.37	27.96
EX83	0.50	**153**	172	12.42	167	9.15	-2.91
EX93	0.53	**105**	119	13.33	122	16.19	2.52
EX103	0.49	**139**	158	13.67	159	14.39	0.63
EX14	0.74	**103**	168	63.11	162	57.28	-3.57
EX24	0.77	**108**	169	56.48	156	44.44	-7.69
EX34	0.74	**111**	167	50.45	170	53.15	1.80
EX44	1.14	**126**	242	92.06	217	72.22	-10.33
EX54	1.06	**96**	168	75.00	160	66.67	-4.76
EX64	0.78	**120**	189	57.50	182	51.67	-3.70
EX74	0.97	**126**	156	23.81	180	42.86	15.38
EX84	0.72	**163**	251	53.99	243	49.08	-3.19
EX94	0.76	**122**	181	48.36	170	39.34	-6.08
EX104	0.69	**158**	246	55.70	222	40.51	-9.76
MTD				**37.04**		**33.83**	**-1.65**

Table 4 Comparison results in the case of $\overline{tt}/\overline{pt} < 0.25$

		HA[16]	MAS[30]		HRA		
instance	$\overline{tt}/\overline{pt}$	makespan	makespan	Dev1%	makespan	Dev2%	Dev3%
EX110	0.15	**126**	135	7.14	131	3.97	-2.96
EX210	0.15	**148**	157	6.08	151	2.03	-3.82
EX310	0.15	**150**	154	2.67	156	4.00	1.30
EX410	0.15	**119**	211	77.31	129	8.40	-38.86
EX510	0.21	**102**	118	15.69	108	5.88	-8.47
EX610	0.16	**186**	204	9.68	189	1.61	-7.35
EX710	0.19	**137**	138	0.73	150	9.49	8.70
EX810	0.14	**272**	330	21.32	287	5.51	-13.03
EX910	0.15	**176**	191	8.52	190	7.95	-0.52
EX1010	0.14	**238**	269	13.03	260	9.24	-3.35
EX120	0.12	**123**	127	3.25	127	3.25	0.00
EX220	0.12	**143**	151	5.59	145	1.40	-3.97
EX320	0.12	145	**144**	-0.69	148	2.07	2.78
EX420	0.12	**114**	161	41.23	121	6.14	-24.84
EX520	0.17	**100**	110	10.00	104	4.00	-5.45
EX620	0.12	**181**	196	8.29	**181**	0.00	-7.65
EX720	0.15	136	**132**	-2.94	144	5.88	9.09
EX820	0.11	**287**	319	11.15	**287**	0.00	-10.03
EX920	0.12	**173**	187	8.09	181	4.62	-3.21
EX1020	0.11	**236**	266	12.71	250	5.93	-6.02
EX130	0.13	**122**	134	9.84	127	4.10	-5.22
EX230	0.13	**146**	151	3.42	147	0.68	-2.65
EX330	0.13	146	**129**	-11.64	154	5.48	19.38
EX430	0.13	**114**	228	100.00	126	10.53	-44.74
EX530	0.18	**99**	111	12.12	110	11.11	-0.90

EX630	0.14	**182**	198	8.79	183	0.55	-7.58
EX730	0.17	**137**	**132**	-3.65	146	6.57	10.61
EX830	0.13	288	**273**	-5.21	288	0.00	5.49
EX930	0.13	**174**	187	7.47	183	5.17	-2.14
EX1030	0.12	**237**	266	12.24	245	3.38	-7.89
EX140	0.18	**124**	137	10.48	138	11.29	0.73
EX241	0.13	**217**	230	5.99	224	3.23	-2.61
EX340	0.18	**151**	155	2.65	167	10.60	7.74
EX341	0.12	**221**	227	2.71	232	4.98	2.20
EX441	0.19	**172**	344	100.00	187	8.72	-45.64
EX541	0.18	**148**	158	6.76	158	6.76	0.00
EX640	0.19	**184**	211	14.67	189	2.72	-10.43
EX740	0.24	**137**	158	15.337	154	12.41	-2.53
EX741	0.16	**203**	206	1.48	214	5.42	3.88
EX840	0.18	**293**	331	12.97	**293**	0	-11.48
EX940	0.19	**175**	195	11.43	191	9.14	-2.051
EX1040	0.17	**240**	276	15.00	253	5.42	-8.33
MTD				**14.09**		**5.23**	**-5.28**

The results show that our approach HRA outperforms MAS in most instances of tables 3 and 4. It can be observed that HA obtained the best results in almost all instances due to the fact that it is an offline heuristic and all information of the scheduling problem is known in advance.

From the results in Table 3, the mean total deviation (MTD) of HRA to HA is 33.83%, which means that HRA does not go beyond HA in makespan. This result is in accordance with our expectations as HRA is not an off-line algorithm but on-line and distributed approach. Compared with an on-line approach (MAS), 55% of the results from HRA are better than MAS, and the MTD of HRA to MAS is -1.65%. Thus, HRA shows better performance in makespan. From the results in Table 4, the performance of HRA is better. Compared with on-line approach, the performance of HRA is better than MAS in 69% test instances, and the MTD of HRA to MAS is -5.28%. Because the MTD of HRA to HA is 5.23%, it shows that the optimization capability of our approach is closed to off-line method. Similar results are obtained for EX110, EX220, EX630, etc. In other instance of EX820, is shows the same performance with HA. Similar results are obtained for EX 620, EX830 and EX 840. By comparing the results, it is clear that HRA exhibits better performance in the case of relatively low $\overline{tt}/\overline{pt}$ ratio. As discussed above, the HRA shows the potential to improve the performance in terms of distributed an on-line scheduling of machines and AGVs.

The Gantt chart of instance EX23 is shown in Figure 10. The numbers in the Gantt chat represent the serial number of tasks. For example, the number “21” in M2 represents the first operation task of job2; the number “21” in AGV1 indicates the first transportation of job2. As can be seen from the Gantt chart, at the time 48, a new round of mutual selection between machines and AGVs starts; two AGVs have the transportation capacity to accept more transportation tasks; and operations “61”, “52” and “32” demand AGVs for transportation. In AGV selection stage, affected by the hormone *H* and loading time, the two AGVs select the operation “61” with the lowest weighted loading time; then in machine selection stage, AGV2 is selected as the winner. Because compared with AGV1, AGV2 can finish the task with lower deviation, and the hormone secretion speed is lower than AGV1. The mean value of transportation task of AGV is 11.2 which can be computed by using the data in Table 1. As shown in the Gantt chart, 21 transportation tasks are implemented by two AGVs, and the distribution of time for AGVs is shown in Figure 11. 90.48% of the transportation tasks have time consumption less than 15. As shown in Figure 12, the utilization rate of two AGVs remains at a high and balanced level.

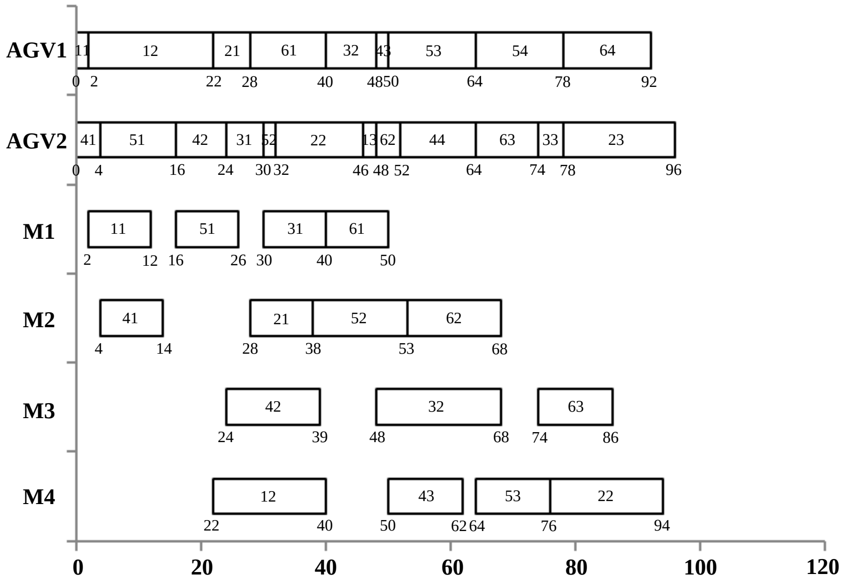

Figure 10 Gantt chart of EX23

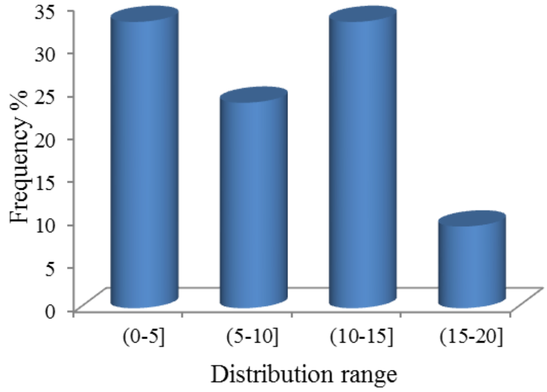

Figure 11 Distribution of time for AGVs

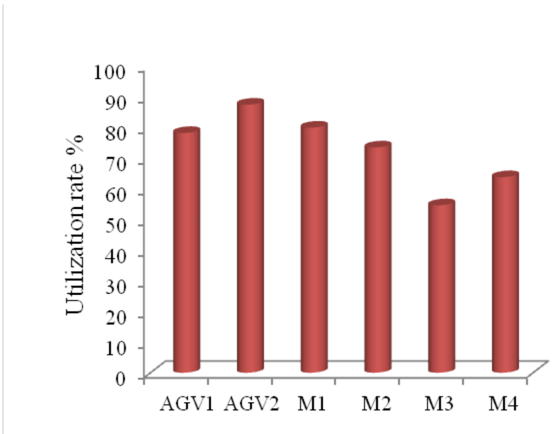

Figure 12 Utilization rates of AGVs and machines

6. Conclusions

In this paper, a hormone regulation based approach for distributed and on-line scheduling of machines and AGVs is proposed. The principle of hormone diffusion and reaction in endocrine system provides a new information processing method for the on-line scheduling model to agilely cope with new arrival tasks. According to hormone-regulation mechanism, the deviations between completion time and planned time in on-line allocation processes are used to optimize makespan. Thus in the mutual selection between machines and AGVs, machines can allocate transportation tasks according to the minimum secretion speed of hormone, and AGVs can select transportation tasks with the highest transportation efficiency. As the tasks are well allocated and good performances of the system can be obtained.

The proposed approach was tested and compared with classical instances in literatures. The performance of HRA was close to off-line approaches. Especially in the low ratio, the performance in some instances was the same with off-line approaches. Compared with the on-line approach, performance of HRA was better in more than half of the test instances, and the rest was the same or close to. The results show that HRA reflects a promising performance in terms of distributed and on-line scheduling of machines and AGVs. The application of hormone regulation in this area shows great potential. Especially its reaction and diffusion mechanisms can quickly respond and satisfy scheduling requirements in the system. And it expands the view of research on dynamic scheduling problems. Future research can be directed towards the decision-making modules in different stages to improve the performances of the scheduling approach. Besides, the proposed approach can be enhanced to take into account conflict, deadlock, delay, recourse malfunction, rush orders, etc.

Declaration of conflicting interests

The authors declare that there is no conflict of interest.

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