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Switching mechanism of dynamic hybrid control multi-agent system in manufacturing environment

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HIGHLIGHTS

- The hybrid model melds semi-heterarchical and hierarchical benefits, enabling adaptive control.
- Switching to semi-heterarchical structures can boost efficiency, especially with operational deviations.
- Implementing semi-heterarchical control yields the most optimal production outcomes.

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ABSTRACT

Current expectations demand that manufacturing control systems exhibit enhanced flexibility and agility. Concurrently, using a multi-agent manufacturing system has been regarded as a crucial strategy for addressing the challenges associated with dynamics and unpredictability within the setting of part processing. This paper presents a novel switching mechanism for a hybrid control multi-agent system. The proposed hybrid control model combines the benefits of semi-heterarchical and hierarchical structures, enabling the successful implementation of adaptive control strategies. The aim is to enhance the implementation of a multi-agent control system in a dynamic manufacturing environment. This study checks how well the suggested switching mechanism in a hybrid control multi-agent system by examining its performance across many metrics, including processing time, throughput, cycle time, and utilization of resources. The results show that a semi-heterarchical control architecture system has superior outcomes to a hierarchical control structure. The evaluation of a production control policy typically necessitates the utilization of simulation modeling, as it involves complex interactions. In this regard, the Matlab 2022/Simulink software package was employed. This study was conducted in response to the limited number of comprehensive studies that have described the implementation of this particular program.

1. Introduction

Firms' focus on customer satisfaction is influenced by both present and future market conditions. Consequently, organizations are motivated to adopt enhanced product customization and prompt responsiveness to sustain their competitive edge [1]. Companies want adaptable production systems that may effectively employ their capacities irrespective of disruptions [2]. Industries have shifted towards Flexible Manufacturing Systems (FMS) due to global economics, technological advancements, and changing customer demands [3]. An effective production control system is necessary to achieve operational efficiency in a competitive industry by efficiently managing all operations and optimizing key performance metrics [4]. Control has gained significant relevance in corporations in recent decades. As a field that provides precise information from different areas of the organization, regulating duties has evolved from being an auxiliary job to a strategic one [5]. In response to the growing number of product variations, there is a demand for more adaptable manufacturing systems. To meet this need, flexible control systems are necessary to manage the flexibility provided [6] effectively. A key component of the industrial control system's architecture is success in FMS. A control architecture describes the component parts, organizational structure, operational features, and dynamic development of a system intended to regulate a manufacturing shop floor [3].

Automated manufacturing systems can be controlled using four different types of architectures: centralized control, hierarchical control, semi-heterarchical (or hybrid) control, and heterarchical (or decentralized) control [7,8]. There is an increasing interest in hybrid control structures that exhibit characteristics of neither centralization nor decentralization [1]. The transition from a hierarchical control structure to a heterarchical or semi-heterarchical control structure can enhance production efficiency, particularly when dealing with deviations from typical operational circumstances [7].

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In the present day, manufacturing systems function within a dynamic context characterized by frequent perturbations and failures. Further investigation is necessary to conduct a comprehensive analysis comparing the two primary control designs, hierarchical and semi-heterarchical control systems [7]. However, to consider the uncertainty arising from dynamic needs, various strategies have been suggested to ensure global objectives and mitigate the negative impact caused by unforeseen changes. Several approaches exist for addressing scheduling challenges in uncertainty, including re-scheduling techniques [3].

The existing literature has reported a wide range of empirical research examining control systems with varying objectives. Pach et al. [9] proposed a new generic hybrid control architecture called (ORCA), or the dynamic Architecture for an Optimized and Reactive Control. If an event prevents the anticipated behavior from being followed, this hybrid architecture can dynamically and partially flip between a hierarchical predictive architecture and a heterarchical reactive architecture. Jimenez et al. [10] introduced a framework for switching mechanisms in dynamic hybrid control architectures. This paradigm concurrently addresses the optimality and reactivity limits of both hierarchical manufacturing scheduling systems and heterarchical manufacturing execution systems, thereby maximizing their respective benefits. Meissner et al. [11] concentrated on decentralized control methods and hierarchies in addition to Industry 4.0's features. Dassisti et al. [8] suggested creating a new Hybrid Control Architecture (HCA) to give a "global view," meaning that the resources used in the manufacturing process should know how to operate to meet the manufacturing system's optimization objective. Mayer et al. [6] introduced a conceptual framework consisting of three key components: a simulation model that represents a modular assembly system, a multi-agent system that integrates control logic, which can be either centralized or decentralized (heterarchical), and an interface designed for the exchange of data. The utilization of priority rules was suggested by Roa et al. [3] to enhance the responsiveness characteristics of a semi-heterarchical management system. Boccella et al. [7] presented a comparative analysis of centralized and heterarchical control structures within a virtual learning environment. The conceptualization and testing of control structures for assembly stations and materials handling systems in industrial systems have been conducted across many operational scenarios.

Grassi et al. [12] introduced a control architecture that is semi-heterarchical, considering three distinct functional levels: (1) Knowledge-Based Enterprise Resource Planning (KERP), which represents the business level and is responsible for cloud interaction, (2) high-level controller (HLC), which is responsible for the overall performance of a monitored system, and (iii) low-level controller (LLC), which is operational between manufacturing control systems and different production systems. Ismayyir et al. [13] provided a literature evaluation on manufacturing control systems and their correlation with various production systems, categorized according to their variety and quantity. Ebufegha [14] employed a Multi-Agent System (MAS) methodology, in which individual entities inside the system process autonomy control to make real-time dynamic scheduling decisions. The study conducted by Salatiello et al. [15] examined the efficiency of a semi-heterarchical control system by implementing a new scheduling method. Two innovative dispatching rules were proposed, each evaluated with varying degrees of unpredictability. To reduce expenses related to operation in the face of uncertainty concerning renewable energy supply and load demand, a decentralized energy management system was developed by Wynn et al. [16]. A novel decentralized event-driven optimal control technique for uncertain linked systems, incorporating unmodeled dynamics, was developed by Zhao et al. [17]. The collaborative adaptive cruise control challenge was formulated by Chen et al. [18] as a task involving Multi-Agent Reinforcement Learning (MARL). A completely decentralized MARL architecture was proposed to enhance efficiency and scalability. Ismayyir et al. [19] presented an analytical methodology for evaluating the performance of production control systems to the volume and variety characteristics of the products being created within the context of the FMS.

The conventional methodology employed in manufacturing control systems has encountered limitations due to its inability to anticipate appropriate responses in dynamic contexts. Manufacturing systems have transitioned from prioritizing maximum efficiency and optimization to focusing on dynamic and customized manufacturing. The existing hierarchical control mechanisms in production systems are no longer sufficient to address the multifaceted demands of the market. Enterprises must establish and maintain an extremely adaptable control system to manage the intricate production environment effectively. This study aims to outline the primary contributions pertaining to the topics above. (1) This study presents a proposed methodology for incorporating an optimization technique into the switching mechanism among hierarchical and hierarchical structures. This allows for executing the control system design in the most appropriate operating mode that meets the requirements of optimality and reactivity. The optimal control architecture is determined by calculating the demand cost for each control architecture. The control architecture with the lowest cost is prioritized and executed first, followed by the other control architectures. This mechanism effectively attains production objectives to enhance profitability and maintain market competitiveness while meeting consumer satisfaction. (2) The suggested approach introduces a self-organizing negotiation mechanism to facilitate cooperation among numerous agents and enhance intelligent decision-making.

2. Control architectures of manufacturing system

Control activities are employed to conduct production control. The coordination of control operations can be effectively linked to controllers, which are structured within an architecture framework. The control architecture directly impacts the efficiency and flexibility of manufacturing [20]. The attainment of flexible production control in assembly systems presents considerable challenges and has conventionally been addressed by centralized and hierarchical approaches. Nevertheless, these methods are accompanied by notable limitations stemming from their inflexible framework [21]. One of the main causes of failures in FMS is the absence of suitable control structures [22].

In a centralized and hierarchical system, control decisions are made in a singular place. The control architecture under consideration is distinguished by a singular component that governs all manufacturing entities, such as robots and handling systems [7]. Hierarchical systems are characterized by many control layers, wherein decision-making authority is spread among these layers. This enhanced robustness is accompanied by a notable decrease in performance due to disruptions [21]. Each manufacturing entity is under the authority of a superior control component, with a single component at the highest level of the hierarchy assuming responsibility for the whole control process. The execution of control operations follows a top-down approach, but generating reports from control activities follows a bottom-up method [7,20]. The conventional approach to complexity management, which involves simplifying and implementing hierarchical levels, has demonstrated less effectiveness when compared to alternative architecture when complexity and size grow [21]. Conversely, heterarchical distributed systems present a paradigm shift that purportedly possesses the ability to handle complexity effectively while exhibiting desired attributes such as adaptability, resilience, and autonomous organization. Heterarchical distributed systems facilitate the integration of low-level decision-making intelligence and autonomy, enabling them to coordinate and interact with mutual entities and the environment effectively. Active central decision-making and hierarchical /layered structure are often absent, as they are replaced by loosely related transitory relationships instead of a specified and fixed structure [21,23].

A semi-heterarchical control architecture is proposed to attain optimal levels with a perturbation, which considers modifications to the control system's design or reconfiguration of the architecture. This strategy alters the level of independence and the method of decision-making, which is particularly crucial for responsiveness in disrupted situations [3]. Semi-heterarchical manufacturing systems seek to incorporate heterarchical systems' benefits into a hierarchical or centralized structure. These systems support or limit distributed decision-making processes while maintaining a hierarchical power structure [21]. The hierarchical arrangement of control components and the associated industrial entities to be regulated remain but with varying degrees of autonomy assigned to the global control component. In this particular scenario, the control components situated at higher places within the pyramid lack a rigid control mechanism at lower levels. However, all control actions are effectively coordinated [7].

3. Multi-agent approach of manufacturing control system

The multi-agent strategy is becoming more prevalent to enhance manufacturing systems' resilience and adaptability in dynamic conditions. Agents represent each element inside a production system, enabling them to communicate autonomously with all other elements. The multi-agent strategy is distinguished by the engagement of communities of agents through message exchange, facilitating the achievement of system objectives [24]. The appropriateness of employing an agent-based methodology is based on the attributes of the production system, including ambiguity in product requirements and disruptions in the process [25]. A multi-agent approach is regarded as the preferred control strategy for manufacturing systems to address these issues. It offers desirable features such as autonomy, responsiveness, social ability, and proactiveness [26].

The issue of manufacturing control can be examined from two distinct perspectives: low-level and high-level. The individual manufacturing resources at the low–level need to be regulated to achieve the unit processes anticipated by the high-level control functions. The field of high-level manufacturing control focuses on coordinating existing manufacturing resources to achieve the necessary quantity of product types. Agent technology is commonly utilized in high-level manufacturing control inside agent-based manufacturing systems, although it may also be implemented at lower levels as well [27].

4. Methodology of dynamic-hybrid control architecture

The control structure of our system is characterized by a balance between decentralization and hierarchy. This study aims to propose a conceptual framework for developing a production control system that incorporates an effective switching mechanism within the context of Dynamic Hybrid Control Architectures (D-HCA). Figure1 illustrates the framework of D-HCA in the manufacturing system.

This approach's control system architecture is divided into three layers: the physical layer, the operation layer, and the coordination layer. The decisional entities in charge of global production optimization, or Global Decision Entities (GDE), are located at the coordination layer; on the other hand, the decisional entities in charge of the operation and responsiveness of the tasks are located at the operation layer. The physical layer contains the tasks and resources of the flexible job shop. Local Decisional Entities (LDE), Resource Decisional Entities (RDE), and Global Decisional Entities (GDE) are the three primary categories of decisional entities that make up this architecture. Every single one of them can sense, process, store, and act as a virtual decision-making entity in a production environment.

The hybrid model has the potential to exhibit characteristics related to a semi-heterarchical or hierarchical structure based upon the specific requirements within the current environment. The adopted switching mechanism between the two control structures is based on figuring out how much it costs for both dynamic orders, which operate the semi-hierarchical control structure, and fixed orders, which operate the hierarchical control structure that interacts with the production environment. The flow shop is considered to have received m manufacturing orders, M1, M2,..., Mm, each with a unique product type, Pi, to define the industrial problem formally. A Master Production Schedule (MPS) created centrally is maintained by cooperation amongst three categories of decision entities: coordinating entities, resource/machine entities, and operation entities (products).

The decision entities at the execution layer (operation layer), known as product entities (Pi) and represented by LDEs, are built using a variety of product types for various production orders. They consist of both material and information components. The hardware that oversees the proper execution of configuration and manufacturing procedures makes up the physical component. The informational component sends production orders to resources so that the control system's key performance indicators (KPIs) may be validated. Machine/Resource The remaining physical components of the operation layer that are outfitted with control and hardware components are called Decision Entities (RDEs). The physical layer carries out production processes. If a decisional system is required, the decision entities of the operation layer are the ones who drive decision changes during disturbances. The hierarchical control approach involves the presence of a global schedule (Global Decision Entities

(GDE) that guides decision-making processes, with production entities striving to adhere to the planned scheduling. Figure 2 displays the hierarchical control structure.

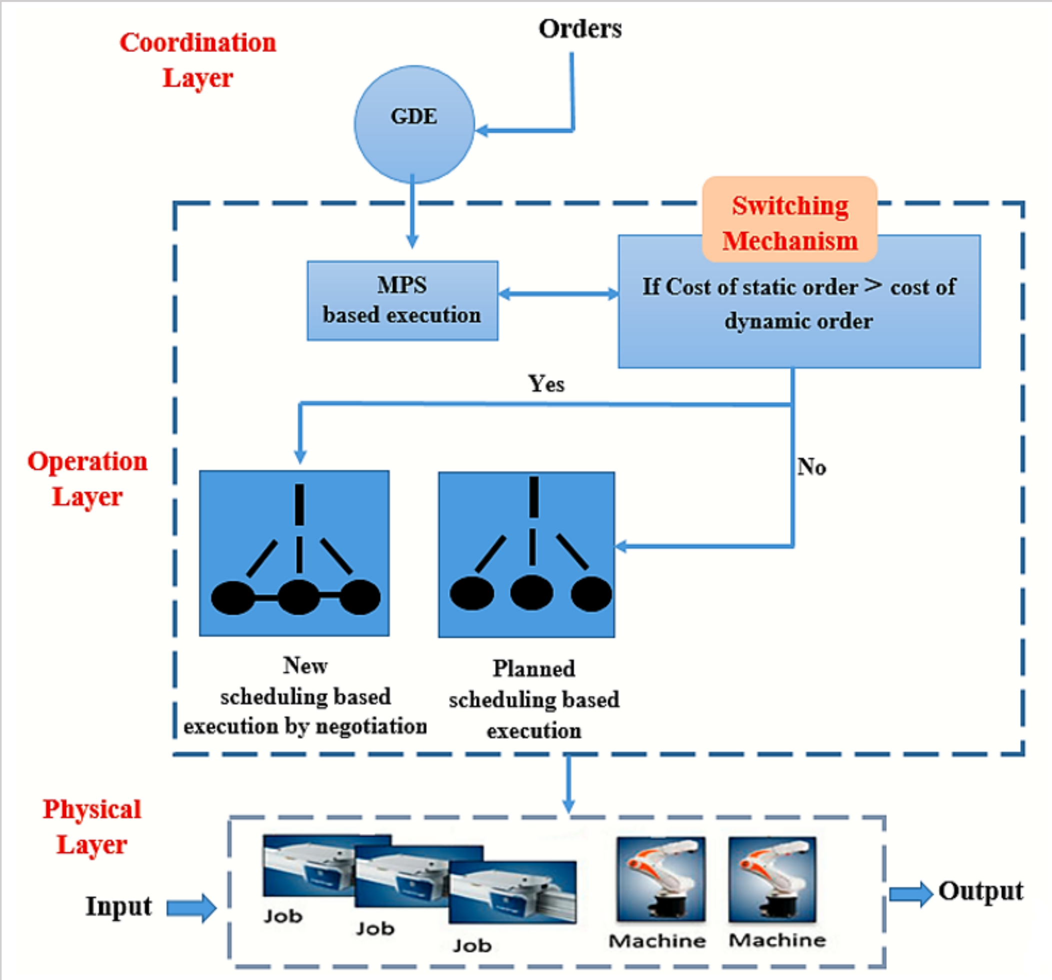


Figure 1: Framework of dynamic hybrid control architectures (D-HCA) of manufacturing system

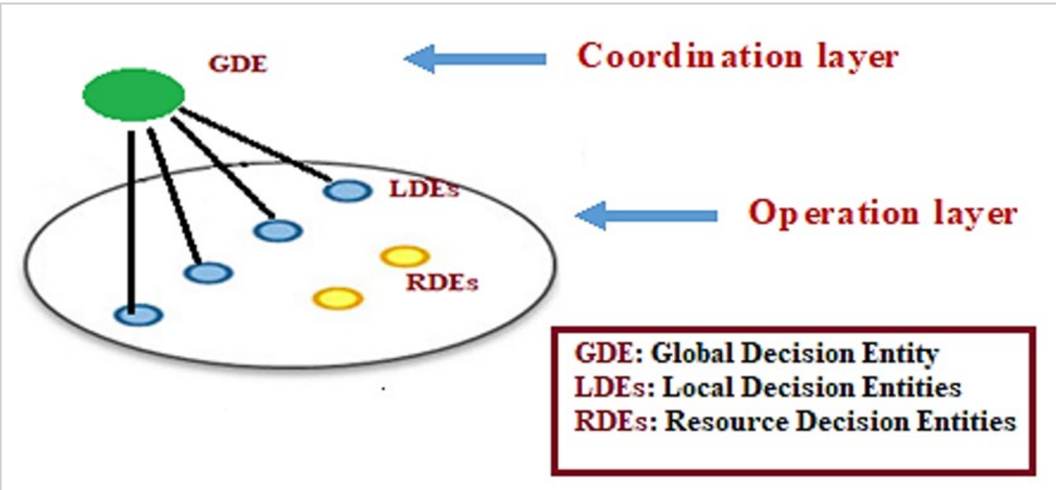


Figure 2: Hierarchical control model structure

As part of the semi-heterarchical control model shown in Figure 3, LDEs function as agents (part agent, machine agent) and decide according to their goals through negotiation between LDEs and RDEs. They also cooperate with a global scheduler (GDE), acting as an optimizer agent to make semi-autonomous decisions in response to dynamic deviations. Unlike hierarchical control, where a single unit handles the scheduling problem, semi-heterarchical control involves collaboration among several entities.

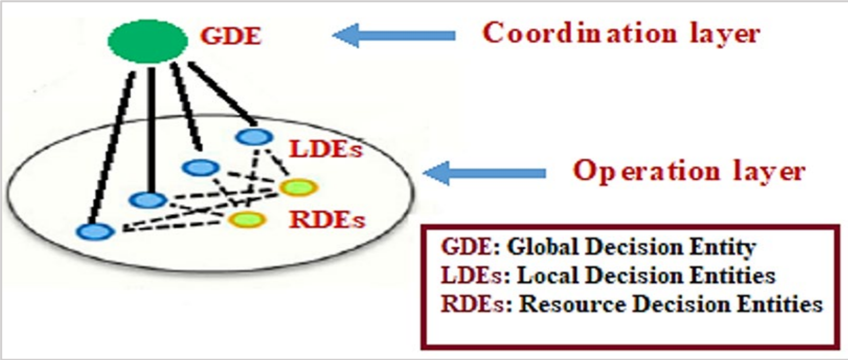


Figure 3: Semi-heterarchical control model structure

In the semi-heterarchical paradigm, all agents can assume the role of decision-makers. The agents can communicate with agents at either the same or different hierarchical levels through horizontal and vertical negotiations. The interaction among agents at different hierarchical levels must adhere to a fundamental principle: agents at lower levels must actively contribute towards attaining objectives set by agents at higher levels, while agents at higher levels must prioritize the interests of agents at lower levels. Hence, in a typical scenario, agents at lower hierarchical levels can independently engage in negotiations while adhering to the boundary conditions established by agents at higher hierarchical levels. Meanwhile, agents at higher hierarchical levels assume responsibility for maintaining the stability of the model.

5. Results and discussion

5.1 Simulation modelling and results discussion

This study aims to assess the effectiveness of hybrid control structures in both normal and perturbed circumstances through simulation modeling. The architecture underwent testing in a simulated environment of the described FMS, which was inspired by a real FMS at the AIP-PRIMECA laboratory at the Polytechnic University of Hauts-de-France. Figure 4 depicts the arrangement of the FMS, while a comprehensive explanation of the system may be found in [28]. The FMS comprises seven assembly machines (robots) interconnected via a conveyor system. It is worth noting that machines M6 and M7 are not employed in this study and have been considered optional. The system can generate seven categories of products (B, E, L, T, A, I, and P), each resulting from a series of 4 to 7 operations.

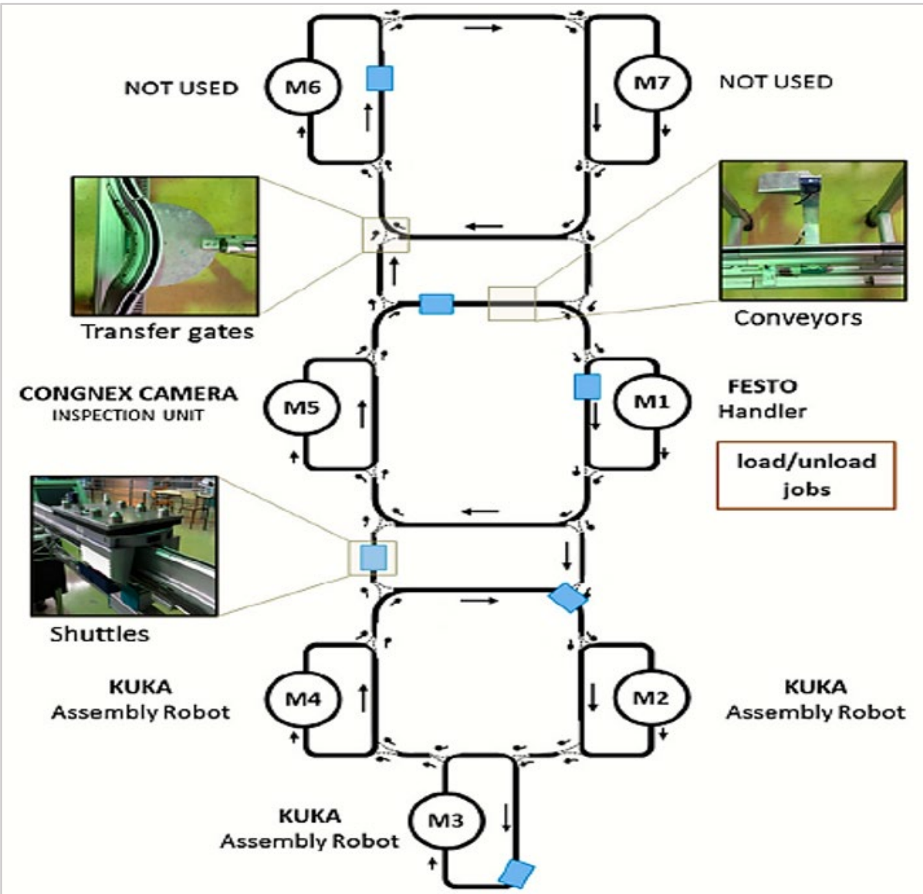


Figure 4: Flexible job shop at the university of polytechnic

Matlab/Simulink software package is utilized to simulate the model of D-HCA, as depicted in Figure 5. The manager agent is responsible for identifying if the received demands fall within the FMS limit in terms of volume and variety. Subsequently, by calculating their respective costs, the coordination agent determines the control architecture based on the lowest cost between the two demands.

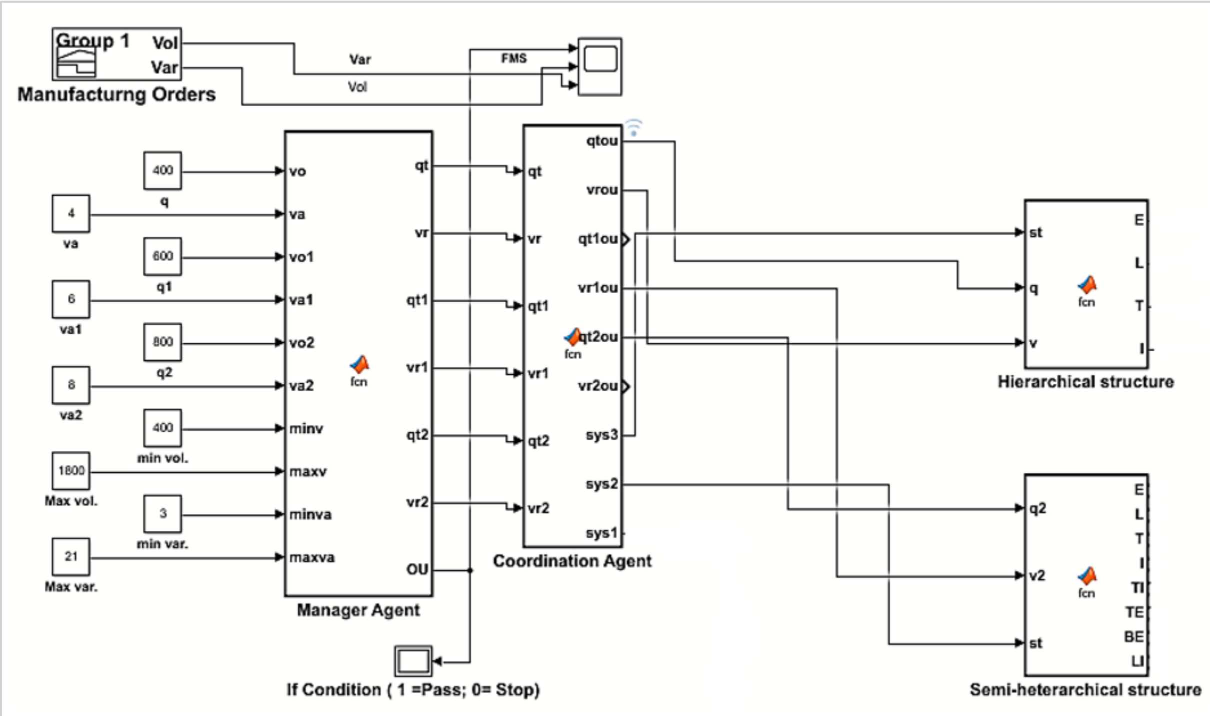


Figure 5: Simulink model of switching mechanism in D-HCA

D-HCA was conducted with the consideration of two distinct scenarios. The initial scenario involved the implementation of a hierarchical control paradigm. A single Global Decisional Entities (GDE) enforces the scheduling algorithm through the global layer in real-time. This ensures that local entities are directed to make decisions that enhance global performance. The scheduling-based rule, First Come First Served (FCFS), has been employed in this case.

To improve the evaluation of the production system's performance in static conditions, it is important to take into account the range of demand variation "var" within the range of 3 to 4, as well as the production volume "vol" within the range of 400 to 700, in accordance with the volume-variety relationship concept of FMS. In this specific situation, we assumed that the demand comprises four separate jobs, specifically (E, L, T, and I), with a demand volume of 2400 production units for these jobs. The launch of these jobs adheres to a pre-established, consistent schedule at regular intervals, with predetermined quantities for every batch. The system has been making predictions about the volume of each part that would be required, assuming no disruptions to the system. Figure 6 illustrates the schedule that will be adhered to until a disruption necessitates a deviation.

```
function [MS1,MS2,MS3]  = fcn(E,L,T,I)

%#codegen

MS1=E*40 + L*40 + T*60 + I*40;
MS2=E*60 + L*40 + T*0 + I*40 ;
MS3=E*20 + L*60 + T*20 + I*0 ;
```

Figure 6: The nominal schedule followed before a disturbance occurs

The second scenario involved the implementation of a semi-heterarchical control model. The warehouse is responsible for staging parts (jobs) and subsequently transporting them to stations during the execution process. Robots, which are versatile resources, are utilized to assemble product components. Based on the manufacturing concept of FMS, customer demand is adjusted in terms of production volume to be between 701 and 1700 production units and the variety of the products to be between 5 and 28. This leads to production-related disruptions. In this particular scenario, the perturbations impact the existing production order scheduling, specifically in relation to the fluctuation in the quantity of the products to be produced. The demand is assumed to comprise eight distinct jobs (E, L, T, I, TI, TE, BE, and LI), with a corresponding demand volume of 7200 production units. The arrival of such jobs has a lower degree of predictability. It adheres to a stochastic trend that is impacted by variations in demand, hence rendering the demand for the product uncertain.

In production, the scheduling algorithms undergo real-time optimization at the local layer, enabling agents to make decisions that improve overall performance. The optimizer agent at a higher level, which has a global perspective, presents two scheduling algorithms: the shortest processing time (SPT) scheduling-based rule and the Nawaz, Enscore, Ham (NEH) scheduling algorithm. These algorithms are used to build a balanced and synchronized order sequence. The lower-level agents, specifically the part and machine agents, rely on the higher-level agents to make resource assignment decisions based on the optimal scheduling algorithm outcomes. The lower-level agents utilize real-time conditions to make decisions through a negotiation process. They propose modifying predetermined resource assignments based on the assumptions outlined in Figure 7.

```
function [M1,M2,M3] = fcn(T,I,E,L,TI,TE,LI,BE)
%#codegen
M1=0;
M2=0;
M3=0;
S=T+I+E+L+TI+TE+LI+BE;
for i =1 :S
   if (M1 <= M2+M3)
      M1=(M1+T*60 + I*40 + E*40 + L*40 + TI*80 + TE*100 + LI*80 + bE*80);
      M2=(M2+T*0 + I*40 + E*60 + L*40 + TI*60 + TE*60 + LI*80 + bE*120);
      M3=(M3+T*20 + I*0 + E*20 + L*60 + TI*20 + TE*40 + LI*60 + bE*60);
   elseif (M1 > M2 && M1 <M3)
      M2=(M2+T*0 + I*40 + E*60 + L*40 + TI*60 + TE*60 + LI*80 + bE*120);
      M1=(M1+T*60 + I*40 + E*40 + L*40 + TI*80 + TE*100 + LI*80 + bE*80);
      M3=(M3+T*20 + I*0 + E*20 + L*60 + TI*20 + TE*40 + LI*60 + bE*60);
   elseif (M1 > M2 && M1 >M3)
      M2=(M2+T*0 + I*40 + E*60 + L*40 + TI*60 + TE*60 + LI*80 + bE*120);
      M3=(M3+T*20 + I*0 + E*20 + L*60 + TI*20 + TE*40 + LI*60 + bE*60);
      M1=(M1+T*60 + I*40 + E*40 + L*40 + TI*80 + TE*100 + LI*80 + bE*80);
   elseif (M2 < M3 && M2 <=M1)
      M2=(M2+T*0 + I*40 + E*60 + L*40 + TI*60 + TE*60 + LI*80 + bE*120);
      M1=(M1+T*60 + I*40 + E*40 + L*40 + TI*80 + TE*100 + LI*80 + bE*80);
      M3=(M3+T*20 + I*0 + E*20 + L*60 + TI*20 + TE*40 + LI*60 + bE*60);
   else
      M3=(M3+T*20 + I*0 + E*20 + L*60 + TI*20 + TE*40 + LI*60 + bE*60);
      M2=(M2+T*0 + I*40 + E*60 + L*40 + TI*60 + TE*60 + LI*80 + bE*120);
      M1=(M1+T*60 + I*40 + E*40 + L*40 + TI*80 + TE*100 + LI*80 + bE*80);
   end
M1=M1+1;
M2=M2+1;
M3=M3+1;
end
```

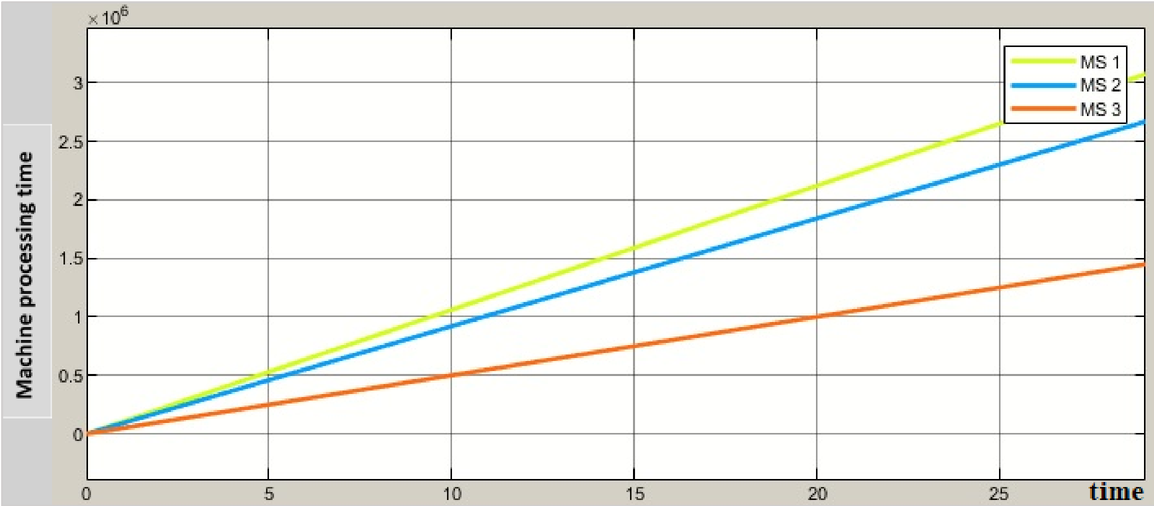
Figure 7: Negotiation of product and machine agents

5.2 Processing time analysis

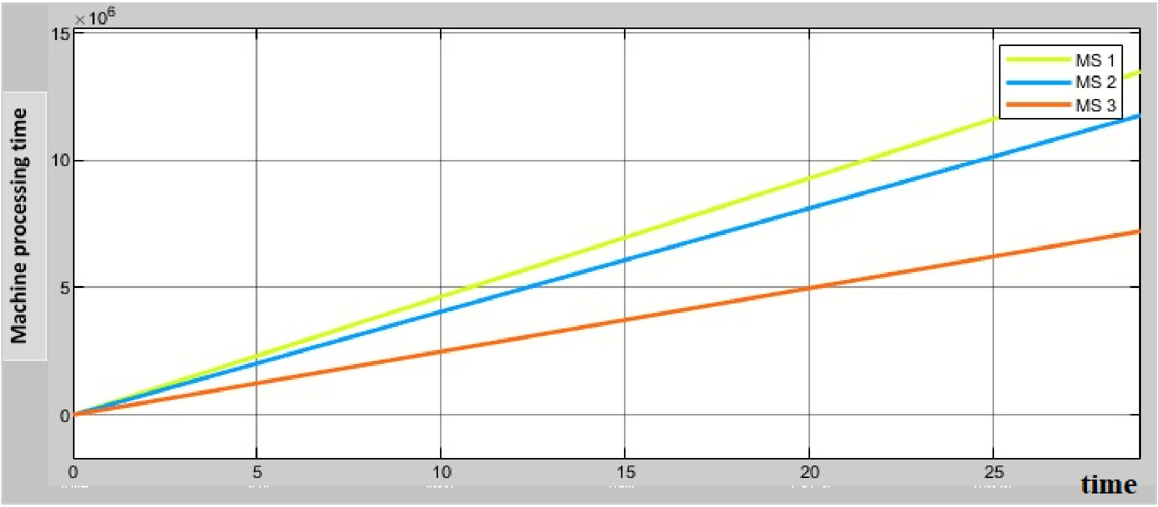
To satisfy market demand, our study employed FMS as a production environment, enabling the manufacturing of various products with minimal setup time. Production enhancement is achieved by implementing an efficient control system in conjunction with automation. The performance of the suggested switching mechanism of D-HCA is evaluated by examining the fluctuations in several metrics, including processing time, throughput, cycle time, and utilization of resources.

The finding indicates that the operation duration on the first machine (M1) exceeds the processing time on the two machines (M2 and M3). This disparity depends upon each product's specific components and their respective operations within the assembly process on each machine. The simulation analysis of job scheduling on three machines (M1, M2, and M3) for hierarchical control structure is illustrated in Figure 8a, while for semi-heterarchical control structure is illustrated in Figure 8b. It is expressed by the Equation 1:

$$\text{Machine processing time} = \Sigma\ (\text{task end time} - \text{task start time}) \tag{1}$$



(a)



(b)

Figure 8: Simulation analysis of processing time for jobs on three machines: (a) hierarchical control structure (b) semi-heterarchical control structure

The processing time on the three machines was influenced by the workload being handled. Specifically, M1 was responsible for handling numerous jobs concurrently, resulting in a more lengthy processing time compared to the workloads of the other two machines. Within a hierarchical structure, the decision-making process is frequently centralized, and subordinate entities rely on decisions made by superior authorities, necessitating approval from these superior authorities. The implementation of a centralized decision-making process may result in delays. At the same time, the imposition of a hierarchical structure for allocating and scheduling jobs through scheduling algorithms may restrict their capacity to adjust to dynamic circumstances promptly.

On the other hand, inside a semi-heterarchical structure, the distributed decision-making process enables expedited replies to job scheduling. In a semi-heterarchical system, the hierarchical structure of command will propose multiple scheduling algorithms to maximize the allocation of resources to process tasks. This allows lower levels of significant freedom in making decisions and selecting the most suitable algorithm for scheduling these jobs. In addition, the allocation of decision-making authority is facilitated by negotiation between the part agent and the machine agent, resulting in expedited replies to job processing requirements at lower hierarchical levels.

5.3 Throughput analysis

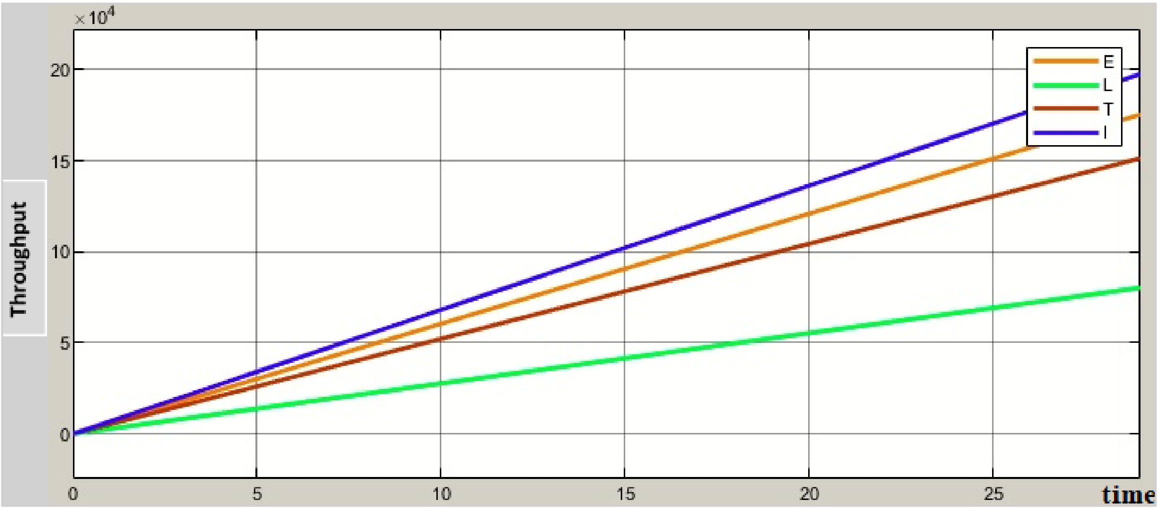
Throughput (TH) refers to the average output generated by a manufacturing process, encompassing many entities, such as machines, workstations, lines, or plants, during a particular period. This measure is commonly expressed in quantities such as parts per hour, expressed by the Equation 2:

$$TH = \sum_{i=1}^{T} Pi/T \quad (2)$$

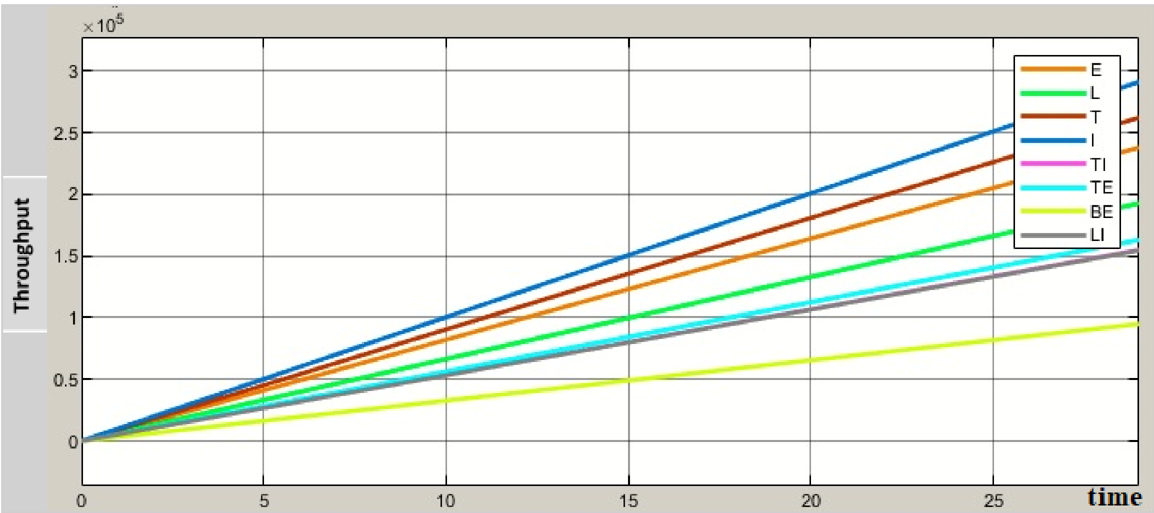
Pi is the number of products produced in time i, and T is the production time. Figure 9a illustrates the simulation findings of throughput performances for hierarchical control structure, while Figure 9b illustrates the simulation findings of throughput performances for semi-heterarchical control structure .

In the hierarchical control scenario, the demand volume for FMS is estimated to be between 400 to 700 units. All four jobs are considered to have a demand volume of 600 units, resulting in a total job quantity of 2400 units. In a semi-heterarchical scenario, the demand volume for FMS production is assumed to fall between the specified boundaries of 701-1700. The demand volume for eight distinct jobs is estimated to be 900 units, resulting in 7200 units.

A semi-heterarchical control system has a good effect on throughput by facilitating decentralized decision-making and dispersed control. Although the manufacturing process took a long time, lasting 525-time units and producing approximately 7200 units, this study demonstrates that implementing a semi-heterarchical control approach significantly improved throughput performance. Specifically, the throughput reached 117 units compared to 69 units in the hierarchical control approach. This improvement resulted in a 70% increase in throughput. Furthermore, implementing higher autonomy and flexibility in semi-heterarchical control at the local level within the production system leads to the emergence of new goods, potentially enhancing overall throughput in the long run.



(a)



(b)

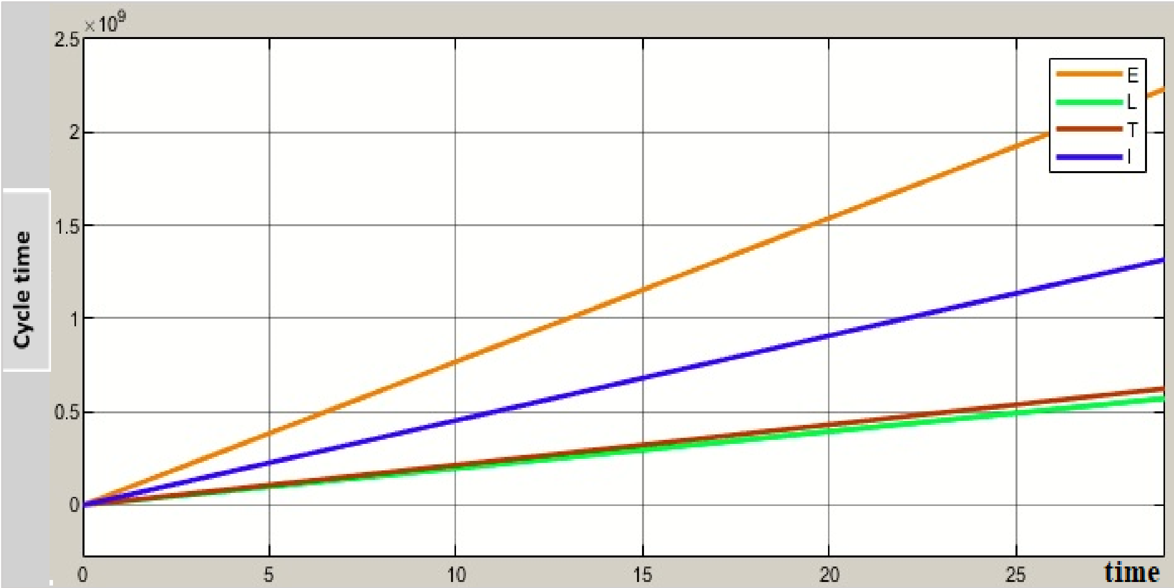
Figure 9: Simulation analysis of throughput parameter; (a) hierarchical control structure, and (b) semi-heterarchical control structure

5.4 Cycle time analysis

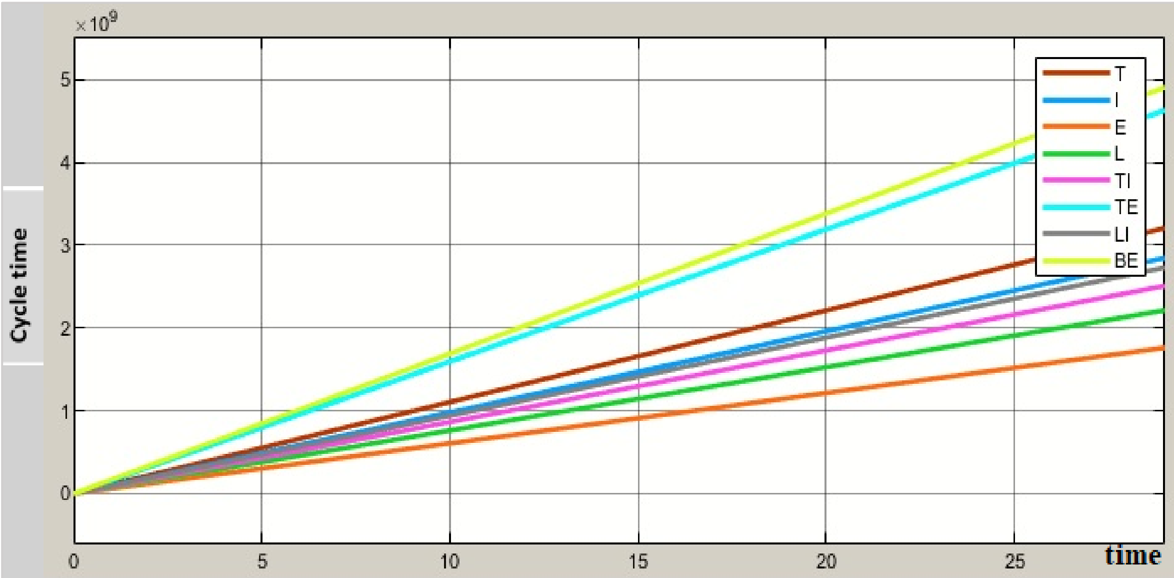
Cycle time was selected as an additional metric to evaluate the effectiveness of the control strategies in combination with the previously examined data on production throughput. Figure 10a shows cycle time for hierarchical control structure, while Figure 10b shows cycle time for semi-heterarchical control structure. Whereas it is depicted as the cumulative duration required for a job to traverse the entire process, encompassing phases such as loading, unloading, processing, transportation, inspection, and changeover times by applying a particular Equation 3:

$$\text{CT} = \text{Operation time} + \text{Idle time} \quad (3)$$

where; Operation time =processing time, Idle time = load/unload time, inspection time, transportation time, and changeover time.



(a)



(b)

Figure 10: Simulation analysis of cycle time parameter; (a) hierarchical control structure, and (b) semi- heterarchical control structure

In contrast to hierarchical structure, semi-heterarchical control has the potential to result in decreased cycle times due to the provision of decentralized decision-making at certain levels. This capability has the potential to provide expedited response to production challenges, enhance collaboration among diverse units, and expedite adaptation to dynamic market needs. In general, the potential to enhance production cycles by reducing delays and increasing overall efficiency.

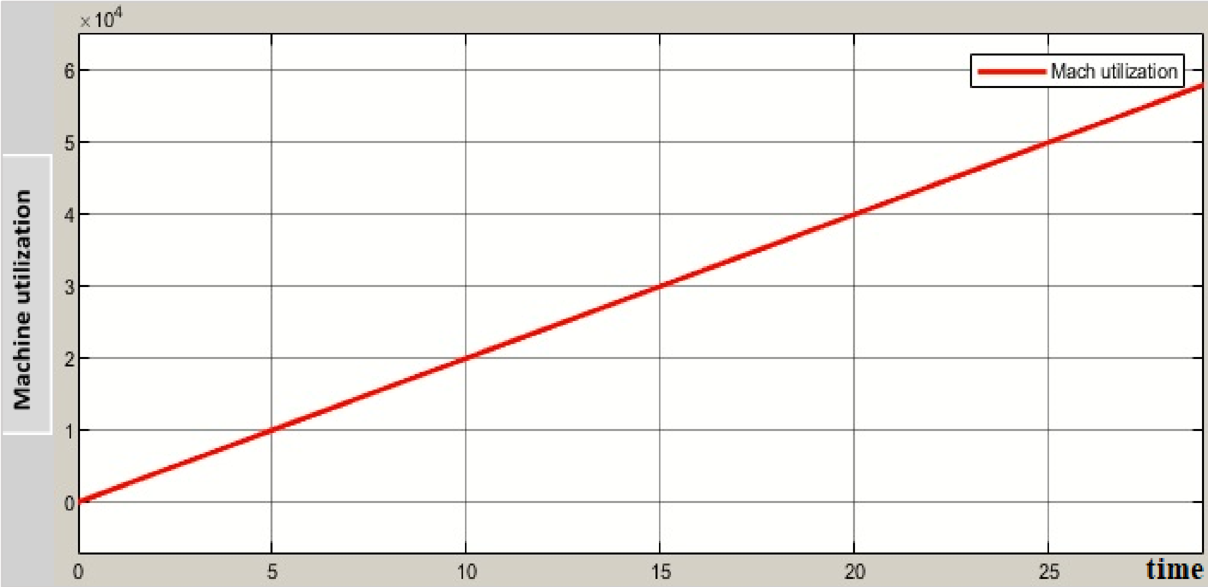
5.5 Machine utilization analysis

A semi-heterarchical control system is employed to ensure optimal utilization of machinery while minimizing costs and resource loss. It can be calculated by the Equation 4:

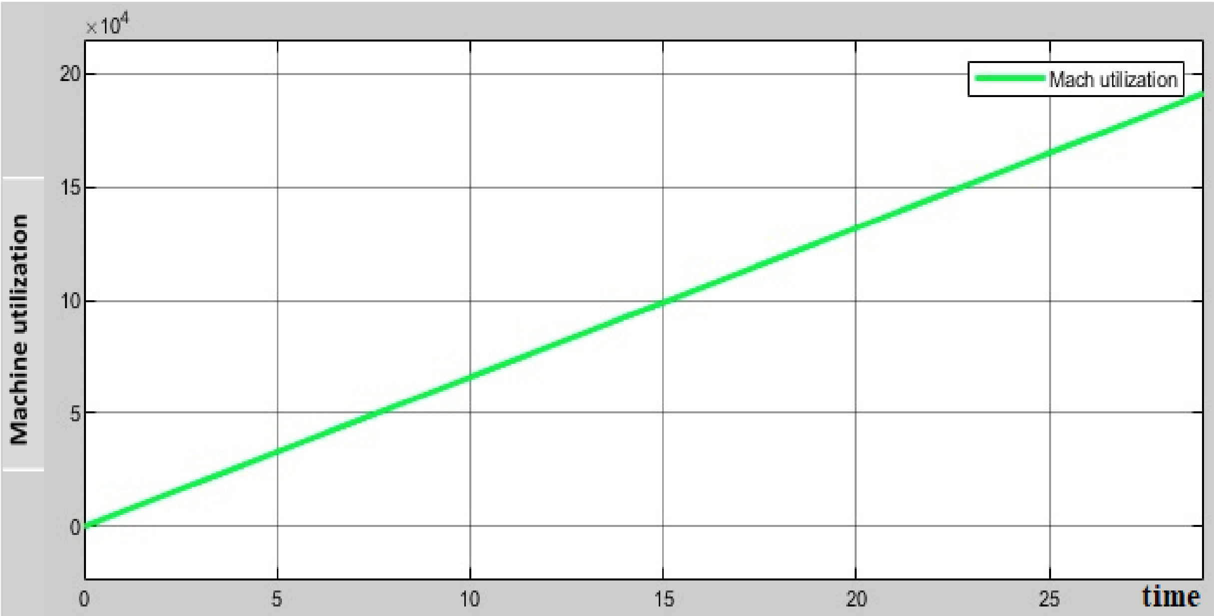
$$MU = \frac{N\,01}{\sum_{k=1}^{nc} Mk \times Ck} \quad (4)$$

where; MU= Machine Utilization, N01= total number of operations within the block diagram form, Mk= number of machines in the kth cell, Ck= number of jobs in the kth cell, nc=number of cells

Operational efficiency can be achieved by enhancing average machine utilization by 7% through dynamic re-sequencing machines based on real-time demand. Figure 11a depicts the analysis of machine utilization simulation results for hierarchical control structure, while Figure 11b shows machine utilization simulation results for semi-heterarchical control structure .



(a)



(b)

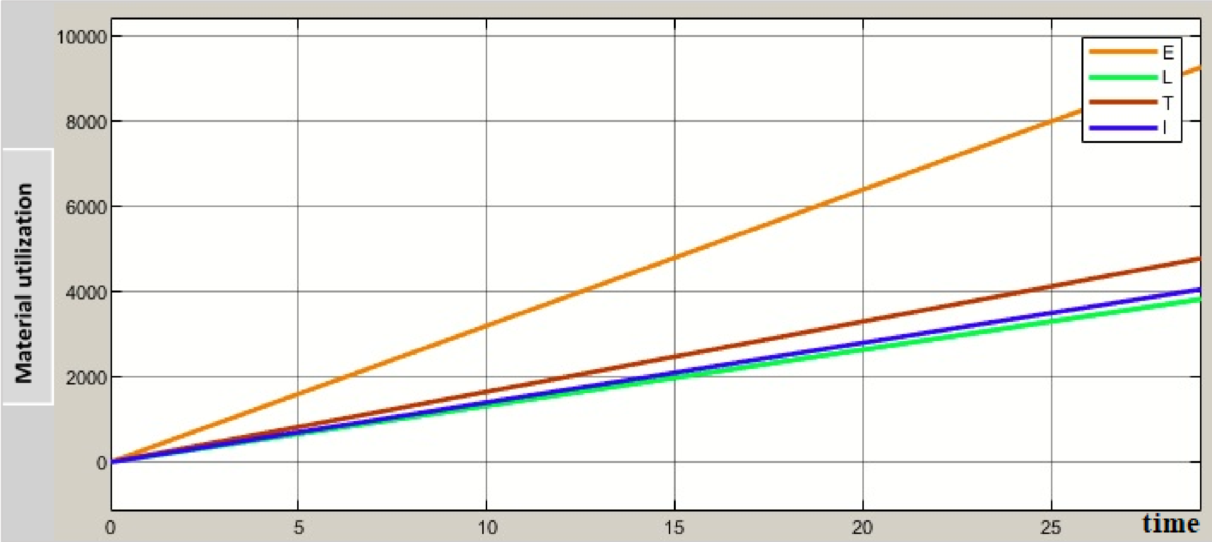
Figure 11: Simulation analysis of machine utilization parameter; (a) hierarchical control structure,and (b) semi-heterarchical control structure

5.6 Material utilization analysis

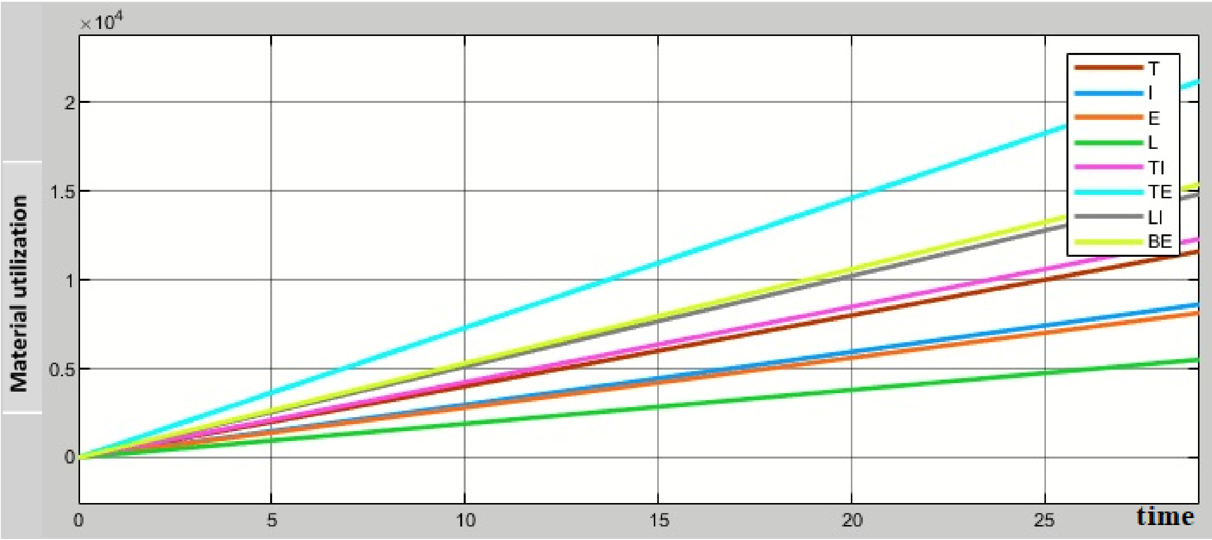
The semi-heterarchical control system demonstrated exceptional performance in terms of achieving optimal resource allocation with low cost and without inefficiency. The following Equation (5) for material usage was applied to produce the previously described metric:

$$\text{material utilization} = \left(\frac{\text{Area occupied by products}}{\text{total plate area}}\right) \times 100\% \qquad (5)$$

Figure 12a indicates material utilization for hierarchical control structure. When numerous products are assembled on the same plate, the findings indicate a 51% increase in the material needed for plates used in component assembly. Figure 12b illustrates the increased utilization of sheets for producing products (TE, BE, LI, and TI) due to combining two products on a plate instead of constructing a single product for the semi-heterarchical control structure. Furthermore, including products (T, I, E, and L) in the assembly process enables various variations to respond to customer demand. Hence, within the framework of manufacturing firms functioning within a competitive market, an exclusive dependence on traditional (hierarchical) production control systems is no longer deemed sufficient to attain operational excellence.



(a)



(b)

Figure 12: Simulation analysis of material utilization parameter; (a) hierarchical control structure, and (b) semi-heterarchical control structure

6. Conclusion

In the increasingly competitive environment of manufacturing organizations, traditional production control approaches are no longer adequate for attaining operational excellence. This work provides a detailed presentation and implementation of a methodology for designing an adaptive production control system. The system is based on shifting between two control system designs (hierarchical and semi-heterarchical). This paper presents a comprehensive overview of the switching mechanism and the necessary considerations for achieving optimal switching. The experimental findings indicate that the most optimal outcome was achieved by implementing semi-heterarchical control. The proposed hybrid control model combines the benefits of semi-heterarchical and hierarchical structures, enabling the successful implementation of adaptive control strategies. It can be easily adjusted to meet various manufacturing objectives, such as meeting customer demand and enhancing company profitability.

Author contributions

Conceptualization, D. Ismayyir and L. Dawood; data curation, D. Ismayyir; formal analysis, D. Ismayyir; investigation, D. Ismayyir; methodology, D. Ismayyir and L. Dawood; software, M. AL-Khafaji; supervision, L. Dawood and M. AL-Khafaji; validation, D. Ismayyir; writing—original draft preparation, D. Ismayyir; writing—review and editing, D. Ismayyir and L. Dawood, and M. AL-Khafaji All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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