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International Conference on Changeable, Agile, Reconfigurable and Virtual Production  
**Embracing complicatedness and complexity with  
Anarchic Manufacturing**

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**Abstract**

As manufacturing is moving from mass production to mass customisation in the age of Industry 4.0, companies are forced to embrace complexity to gain a competitive advantage using the emerging paradigm of digital smart manufacturing. However, with this increasing complicatedness and complexity, traditional hierarchical and centralised models may not be suited to schedule and control the shop floor. The Anarchic Manufacturing system, which is an extremely distributed manufacturing system where decision making authority and autonomy is designated at the lowest level between system elements, is a potential solution to the scheduling and control problem. This paper demonstrates the relative performance of a hierarchical system against an Anarchic system. In a simulated model of a manufacturing system, the capability of each machine is reduced to increase complicatedness and the number of secondary resources required to complete an operation is increased to increase complexity and the performance of the two systems are compared. It is shown that under certain circumstances the Anarchic system performs better than the hierarchical system as complicatedness and complexity increase.

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*Keywords:* distributed manufacturing; complexity; agent based modelling; simulation

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**1. Introduction**

Modern manufacturing is becoming increasingly complex, with market demands for improved quality and speed of production whilst increasing customisation. Industry 4.0 proposes flexible future smart factories to meet these demands, utilising advanced digital technologies and systems such as the Internet of Things [1] and Cyber Physical Systems [2]. These digital technologies aim to improve connectivity and communication, enabling the automation of difficult and complex decision making.

Centralised decision making considers all system elements aiming to solve for all constraints simultaneously, however, as the system becomes over constrained the centralised system's performance reduces [3]. Complexity, arising from large hierarchical control architectures and a lack of fault tolerance, has increased the development of decentralised production control systems [4]. Decentralised decision making is viewed as a highly disruptive and key principle of Industry 4.0 [5].

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This paper investigates the performance of a hierarchical centralised system against a distributed Anarchic system as complicatedness and complexity increases. To determine whether the Anarchic system warrants further investigation to solve complex manufacturing problems. The Anarchic Manufacturing system is the most extreme distributed system, where decision making authority and autonomy are at the lowest level without centralised control or oversight.

## 2. Background

‘Anarchy’ is a distributed heterarchical structure, where system elements autonomously interact and communicate with each other, sense their environment and make decisions [6]. There is no central oversight or control, rather the system elements pursue individual goals that creates a macro emergent productive society. The Anarchic system is underpinned by emergent synthesis, where individual agents pursue personal objectives to globally solve unclear problems [7], and could be a solution to very complex manufacturing problems, overturning ‘simplify to improve’.

A free market architecture is used in the Anarchic system, where members of the manufacturing society aim to maximise their own profit, creating a globally efficient system; similar resources compete against each other to offer their services for jobs to complete necessary operations.

Multi Agent Systems (MAS) are increasingly researched as potential solutions for future manufacturing systems, with applications ranging from enterprise integration and collaboration, to shop floor control and planning [8]. Anarchic systems are an example of MAS, here temporary coupled agents collaborate to solve global problems.

Manufacturing complexity is poorly defined, many definitions attempt to classify types of complexity, such as dynamic and structural, or use entropy and heuristic approaches to quantify complexity [9], [10]. Elmaraghy considers the degree of uncertainty as the sliding scale of complexity, moving from simple to complicated to complex and chaos [9]. Many of the complexity definitions incorporate the manufacturing system’s operations and outcome, rather than just the problem the system is trying to solve. Increasing constraints and reducing flexibility increases system complicatedness, Kuzgunkaya compares several manufacturing system configurations and states reduced versatility and flexibility of resources increases system complexity [10]. For branch and bound techniques, each additional constraint creates a new branch to solve for, increasing the solving complexity. Considering an entropic definition of complexity [11], as the number of agents or number of shared resources required per operation increases, the number of states the system can be in rises exponentially, denoted as  $O(a^N)$  an exponential complexity problem. There are known NP-hard problems in manufacturing, such as job shop scheduling [12].

## 3. Experimental framework

The experimental framework compares hierarchical and Anarchic manufacturing systems as system constraints increase. Only two parameters are varied for clarity, these are reducing machine capability to increase complicatedness and an increasing number of resources required to complete an operation to increase complexity.

The Anarchic Manufacturing system follows the same structure defined by Nassehi and Ma [6] with some changes; the system uses a free market architecture [13] and a permutation of Kádár’s contract net protocol with cost factor negotiation [14]. The system modelled only uses a single currency to allocate resources.

A bidding system allocates resources to jobs, based on the resources’ calculated cost and the job’s cost threshold for that operation. A job is given a budget to purchase the services of resources for all operations required. The job tenders its next operation to capable resources, these resources bid and if the lowest bid is below the job’s cost threshold, the resource is assigned the operation. If unsuccessful, there are up to five rounds of bidding, between bidding rounds resources lower their cost and jobs increase their cost threshold; adjustments reflect their bidding success.

Job  $k$  requiring capability  $j$ , denoted as  $J_{kj}$ , calculates its cost threshold by allocating a proportion of its budget to spend, by dividing budget by operations outstanding, and its rebidding threshold increases by the number of unsuccessful tenders. A binary function is used to indicate whether capability  $j$  is required by job  $k$  at time  $t$ :

$$J_{kj}(t) = \begin{cases} 1 & \text{if job } k \text{ requires capability } j \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

Resource cost allocation differs from Nassehi and Ma's [6]; resource  $i$  of capability  $j$ , denoted by  $R_{ij}$  and presented using a binary value:

$$R_{ij} = \begin{cases} 1 & \text{if resource } i \text{ requires capability } j \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

The expected queue length for resource  $i$  is calculated by:

$$\varphi_i(t) = \sum_{j=1}^{n_c} \frac{\sum_{k=1}^{n_j} J_{kj}(t)}{\sum_{i=1}^{n_m} R_{ij}} \quad (3)$$

Where  $n_c$  is the number of different capabilities in the system,  $n_j$  is the number of jobs and  $n_m$  is the number of resources. The expected queue resulting from each capability is the total number of jobs that require that capability divided by the number of similar resources that offer that capability.  $\varphi_i$  sums the expected queues for all capabilities offered by resource  $i$ .

The resource then calculates initial bidding cost ( $\lambda_i$ ) at time  $t$  based on: recent utilisation ( $\omega_i$ ) and expected utilisation from current queue jobs ( $\psi_i$ ) and future expected queue size ( $\varphi_i$ ), all weighted against a queue length contribution factor (6 jobs), utilisation contribution factor (5), expected cost ( $\lambda_0$ ) and a cost surplus factor ( $\rho$ ) enabling profit making.

$$\lambda_i(t) = \rho \lambda_0 \left( \frac{\omega_i(t)}{5} + \frac{\psi_i(t) + \varphi_i(t)}{6} \right) \quad (4)$$

On rebidding at time  $t$ , resources reduce their bid by a cost reduction ( $\sigma_i$ ); calculated based on recent bid success ( $\gamma_i$ ) and current queue ( $\psi_i$ ) relative to expected queue ( $\varphi_i$ ), factored against the maximum bid reduction ( $\sigma_{max}$ ):

$$\sigma_i(t) = \sigma_{max} \left( 2 - \frac{\psi_i(t)}{\varphi_i(t)} - \gamma_i(t) \right) \quad (5)$$

For an extended resource chain, where additional shared and non-coupled resources are required, the Anarchic system repeats the bidding mechanism between resources. Using the negotiated cost between the job and resource 1 plus surplus budget accrued by resource 1, each resource tenders and negotiates the next resource along the chain.

The hierarchical system modelled uses a centrally coordinated dispatch rule allocating a job to the next available resource with the appropriate capability, which are processed on a FIFO basis. Availability is estimated by queue length, as all operations the same average duration. For multiple resource scenarios, the job is allocated to resource 1 which is then allocated to resource 2, via the same dispatch rule.

Fixed parameters levels were selected to enable any possible emergent system behaviour, by creating a stable steady state environment with significant agent activity whilst reducing noise. The scenario selected was a job shop variant, where jobs arrive in batches with several operations to complete and resources have multiple and overlapping capabilities. Operation durations were determined from a random uniform distribution, operation capability requirements were randomly allocated. For the Anarchic system all jobs were given the budget of the expected average cost for all operations. A summary of parameter levels is shown in Table 1.

Global information available to both systems include: number of resources, number of resources of each capability, capability required of the jobs' operations. Variable parameters reflect an increasingly complicated and complex system, by reducing flexibility through reducing resource capability and increasing the number of shared resource types

Table 1. Fixed parameter levels

Fixed parameter	Level
Operations / Job	4 operations
Average operation duration (random uniform distribution)	15 ( $\mathcal{U}[10, 20]$ )
System utilisation (denotes Job arrival rate)	68%
Number of operation classifications (capabilities)	16
Number of Machines	16
Number of Technicians	16

required respectively; these reflect real world challenges. Job operations were assigned a capability, of which operating resource(s) must have. The resource capability parameter ( $\alpha$ ) was denoted by the proportion of all capabilities covered by machine resources; reflecting specialised machines for more difficult operations or lower cost less flexible resources. The number of resources parameter required per operation ( $\beta$ ), machine and technician, was extended by a reducing technician's capabilities, see Table 2 for variable parameter levels.

Table 2. Variable parameter levels

Variable parameter	Levels
Machine capability coverage ( $\alpha$ )	1 (all capabilities), $1/2$ , $1/4$ , $1/8$
Number of resources (technician capability coverage) ( $\beta$ )	1, 2 (technicians $1/2$ capable), 2 (technicians $1/4$ capable)

Twelve experiments were run at four levels of variable parameter  $\alpha$  (machine capability) and three levels of parameter  $\beta$  (number of resources and technician capability), each experiment was run ten times. Each run had identical random number inputs for direct comparability. Experiments were conducted on the AnyLogic 8 platform, which utilises an agent based framework with discrete event decision making logic within agents.

#### 4. Results and discussion

Simulation results, analysing Work In Progress (WIP) and job waiting time, suggest the Anarchic system adapts better to increasing complexity as the resource chain increases, although both deteriorate equally as complicatedness from constraints increase. Simulations record WIP and job waiting time as Key Performance Indicators (KPI), reflecting the system state and the job's perspective; both have a lower the better measurement. WIP results, smoothed with a rolling average and then averaged for all runs, seen in Figure 1. Job waiting time was plotted on histograms with an 80-percentile marker, shown in Figure 2. Practical implementation considerations not with standing, both systems are directly comparable; as one is not significantly more sophisticated or provided unfairly advantageous information.

The Anarchic system is expected to have superior job allocation, due to better foresight. Considering a contrived scenario of two machines, one of capability 'A' and the second of 'A' and 'B', and ten jobs, the first four with capability requirement 'A' and the rest 'B'. The hierarchical system would allocate the first four jobs evenly and the remaining to machine 2; whilst the Anarchic would consider all upcoming jobs and allocate the first four to machine 1 and the rest to machine 2, this is allocatively more efficient and applied in a more realistic and complex scenario for this paper.

WIP results show that as variable parameters  $\alpha$  and  $\beta$  increase, both hierarchical and Anarchic systems' performance deteriorates, however, the hierarchical system deteriorates more as  $\beta$  and complexity increases. For  $\beta$  level 1, there is no clearly discernible difference. However, an addition to the resource chain immediately causes the hierarchical system to perform worse. This is extended as the secondary resource's capability reduces ( $\beta = 2$  with technician at  $1/4$  capability) and maintained as (machine capability) reduces.

The Anarchic's superior performance as parameter increases and maintained as increases suggests that both systems are comparable as the system becomes more complicated, however, as complexity increases the Anarchic can manage coordination complexity better. Increasing the number of resources required along the resource chain significantly increases the relative complexity from an  $O(a^1)$  to  $O(a^2)$ . As  $\alpha$  (machine capability) rises complicatedness increases, and the deteriorating performance difference is maintained; which hinders the flexibility of both systems in

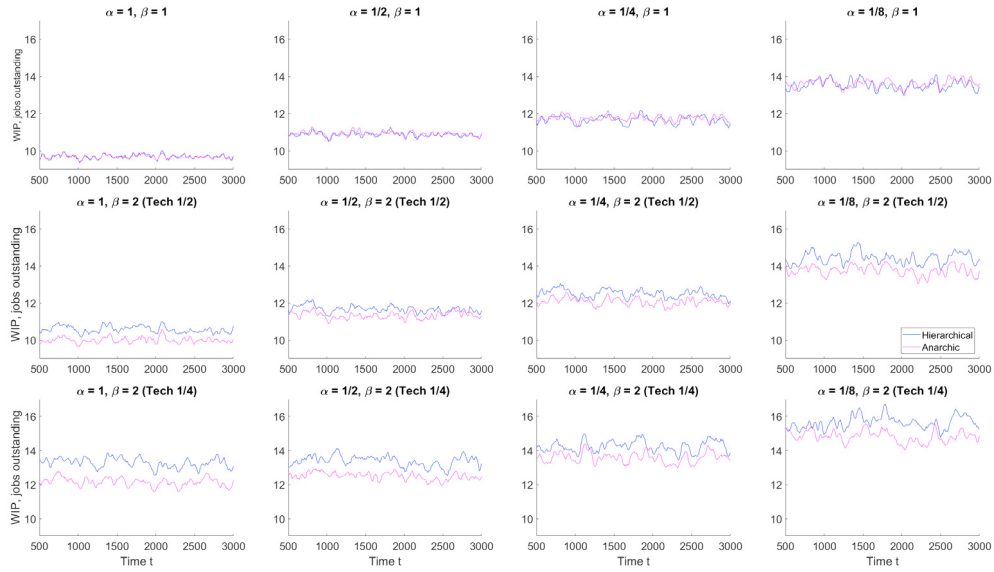


Fig. 1. Work in progress results

a similarly. At  $\beta = 2$  (Technician  $1/4$  capability), the most complex parameter level, there is a significant difference, as shown in Figure 3 where for two experiments the 95% confidence interval of the ten runs is plotted.

The distribution of job waiting time is largely similar for hierarchical and Anarchic systems, particularly in the worst performing scenarios, during less constrained scenarios the hierarchical system performs slightly better. Waiting time impacts a manufacturer’s service level, typically denoted by fulfilling a percentage of orders within a specified time. Service level contributes to the metric On Time In Full (OTIF) [15], where there is a greater desire to avoid lateness rather than promote fulfilling early. The 80-percentile marks, shown in Figure 3, are broadly similar; however, at the most constrained case of  $\alpha = 1/8$  and worst performing, both systems perform very similarly. Suggesting that system constraints impact waiting time, but as waiting time becomes a crucial factor both systems perform similarly.

The results indicate that as complexity increases, the Anarchic system is likely to be able to deal with complexity and perform better. This is likely to be true for increasingly uncertain scenarios that move from complicated to complex and chaotic, the Anarchic should be more adaptable; this is yet to be tested directly and will be during future work.

### 5. Conclusion

This paper investigates how hierarchical and Anarchic manufacturing systems react to increasingly complicated and complex scenarios, it concludes that the Anarchic system performed better under an increasingly complex scenario, warranting further investigation; both systems performed similarly as complicatedness increased. WIP was used as the predominate KPI, although job waiting time provided some insight both systems performed very similarly during worst-case scenarios. Under certain circumstances Anarchic manufacturing systems are shown to have meaningful

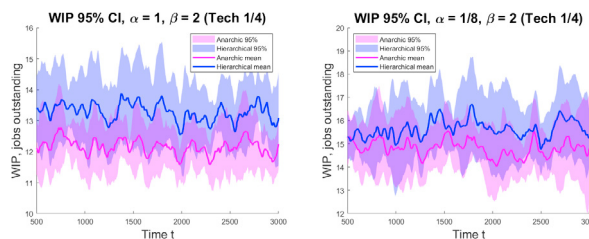


Fig. 2. Work in progress confidence intervals

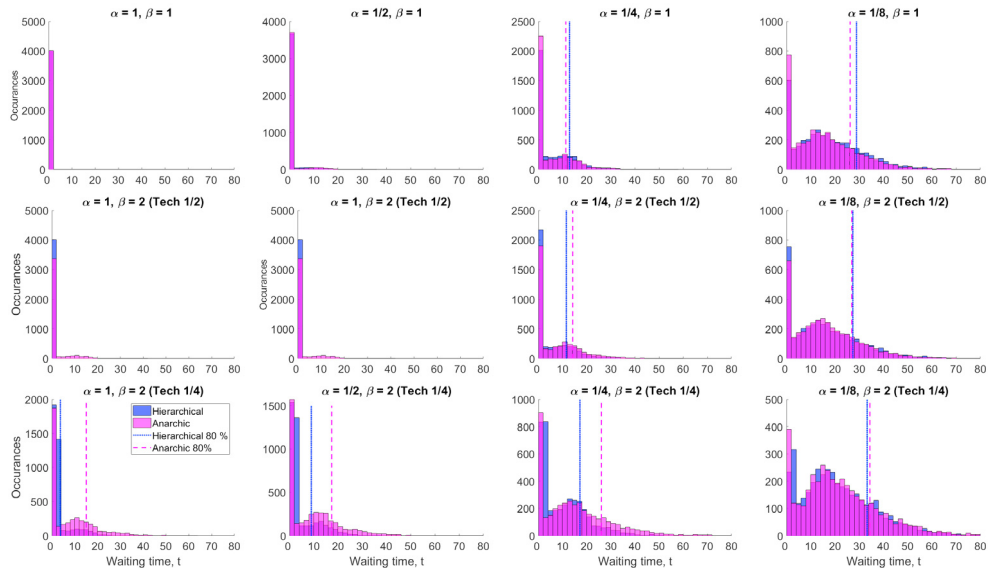


Fig. 3. Job waiting results

improvement in dealing with complexity; this paper increases complexity as an addition to the resource chain. Both systems deteriorated similarly as complicatedness increased, modelled as increasing constraints. Future work will further investigate Anarchic Manufacturing systems; by understanding how chaos can be used to solve very complex problems and challenge the generally accepted practice of 'simplify to improve'.

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