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Anarchic Manufacturing & Mass Customisation

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Abstract

Smart manufacturing has been heralded as the future of manufacturing with cloud-based manufacturing as the latest paradigm. One of the very challenging smart manufacturing objectives is providing mass customisation for which product variability and scale are key factors to manage. These factors are evaluated in this paper against different scheduling and control structures through agent-based simulation modelling. The model demonstrates that Anarchic Manufacturing, or controlling the production in complete absence of hierarchy offers improved performance as the scale increases, and traditional methods to manage complexity, by establishing hierarchical cell structures, significantly detriment performance under certain circumstances. Anarchic Manufacturing is an extremely distributed planning and control system based on the principles of the free market; it benefits from high scalability and emergent outcomes of self-organisation and high adaptability to complexity.

Keywords: Mass customisation, scheduling and control, distributed systems, simulation

1. Introduction and background

Smart manufacturing aims to bring a manufacturing revolution by marrying digital technologies to physical manufacturing operations, one goal is providing mass customisation. These smart manufacturing digital technologies include digital twins, cyber physical systems and the internet of things (Mourtzis *et al.*, 2015; Monostori *et al.*, 2016; Uhlemann, Lehmann and Steinhilper, 2017). Recent manufacturing system paradigms have shifted their focus; from production maximisation to cost reduction, process standardisation to mass customisation and production-centric to service-oriented (Lu, Xu and Xu, 2014). Smart manufacturing business objectives aim to satisfy greater demand volatility, mass customisation and accommodate non-manufacturing concerns e.g. social and environmental. One of the most challenging is mass customisation; providing custom goods and services at mass production prices, but this has yet to be fully realised (Ferguson *et al.*, 2018); partly because variants drive complexity (Vogel and Lasch, 2016). Cloud Based Manufacturing (CBM) is proposed to achieve mass customisation.

CBM can achieve mass customisation, through enhanced flexibility arising from its structure and the participants' diversity and scale; CBM mirrors networked manufacturing supply chains. CBM is a very recent manufacturing paradigm, providing a differentiated offering as a manufacturing service-provider, through its distributed structure, created from a share-to-gain philosophy (Wu *et al.*, 2013); however, individual participants still pursue their individual objectives. A vast number of disparate and diverse manufacturing enterprises participate in a cloud marketplace environment, offering their services which are consumed by individuals.

Manufacturing service providers create temporary loosely coupled reconfigurable production lines to flexibly adapt to unpredictable demand. Service provider participants, often Small and Medium Enterprises (SMEs), are able to focus and specialise on their core operations (Leitão, 2009). CBM can reflect a networked manufacturing supply chain, for example aerospace manufacturing which has many diverse and tiered suppliers; the whole manufacturing supply chain may participate in a private or community cloud environment (Lu, Xu and Xu, 2014).

Manufacturing scheduling and control is traditionally centrally managed; however, this is not necessarily the best for smart manufacturing or CBM scenarios. Hierarchical and centralised structures typically have a master / slave relationship, and use structure to handle complexity through decomposition and simplification (Heragu *et al.*, 2002); for example, by creating hierarchical cellular structures. It is often postulated that traditional hierarchical structures may not be well suited to manage the state-of-the-art hyper-connected smart factories due to their reliance on communication between management layers. Alternative heterarchical structures provide a radical approach; one such system described and used in this paper is Anarchic Manufacturing; there is no central control or oversight, all system elements pursue their own objectives and have decision-making authority and autonomy (Nassehi and Ma, 2017).

Fulfilling mass customisation in cloud based manufacturing creates a number of unanswered research questions, their combined characteristics creates a very complex and difficult scheduling and control problem. Mass customisation provides highly customised products, resultantly the operations required have a high degree of variability and uncertainty; this drives complexity. Additionally, in CBM there is a high diversity of resources providers and the scale is vast with hundreds of thousands of participants (Liu *et al.*, 2018), scale itself drives complexity. Taking an entropic view of complexity, the number of possible states increases exponentially with scale, thus making scale an exponential complexity problem (Elmaraghy *et al.*, 2012); denoted in big O notation as $O(a^N)$. This paper evaluates how three scheduling and control architectures react to increasing job customisation and increasing scale; simulated as increased variability in operation duration and capability required, and scale is increased twice and twenty-fold. The three selected architectures are: hierarchical (cell structure), centralised and Anarchic; as highlighted in Figure 1, the colours refer to results in Section 5. The heterarchical with mediator architecture was not evaluated, as it is most suitably used where distributed mechanisms, here via the free market, are insufficient to a specific problem e.g. rush jobs; no such scenarios were run, therefore this structure was not evaluated.

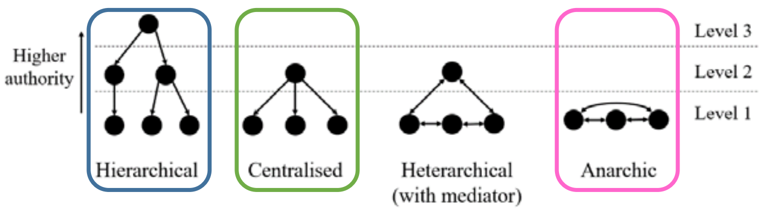

Figure 1 Scheduling and control structures

This paper has five further sections, the next describes and walks through Anarchic Manufacturing systems at a high level, section 3 briefly describes the hierarchical cellular and centralised structures compared in this paper. Section 4 provides the experimental framework, section 5 the results and discussion before the final concluding section 6.

2. Anarchic Manufacturing systems

The Anarchic Manufacturing system is a radical alternative to traditional scheduling and control methods, utilising an extremely distributed structure in a Multi-Agent System. The system follows the structure defined by Nassehi and Ma (2017); the system uses a free market architecture (Dias and Stentz, 2000) and a permutation of Kádár's contract net protocol with cost factor negotiation (Kádár and Monostori, 2001). However, in this paper the system only uses one currency to allocate Machine Tools (MTs). A tendering system allocates MTs to jobs, based on the MT's 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; for its next operation a job allocates an expenditure it is willing to spend as its threshold. The job tenders its next operation to capable MTs, these MTs bid and if the lowest bid is below the job's cost threshold, the MT is assigned the operation. If unsuccessful, there are up to five rounds of bidding, between bidding rounds MTs lower their cost and jobs increase their cost threshold; adjustments reflect bidding success and inclination to take risks respectively. The flowchart in Figure 2 diagrammatically shows the tendering process to allocate jobs.

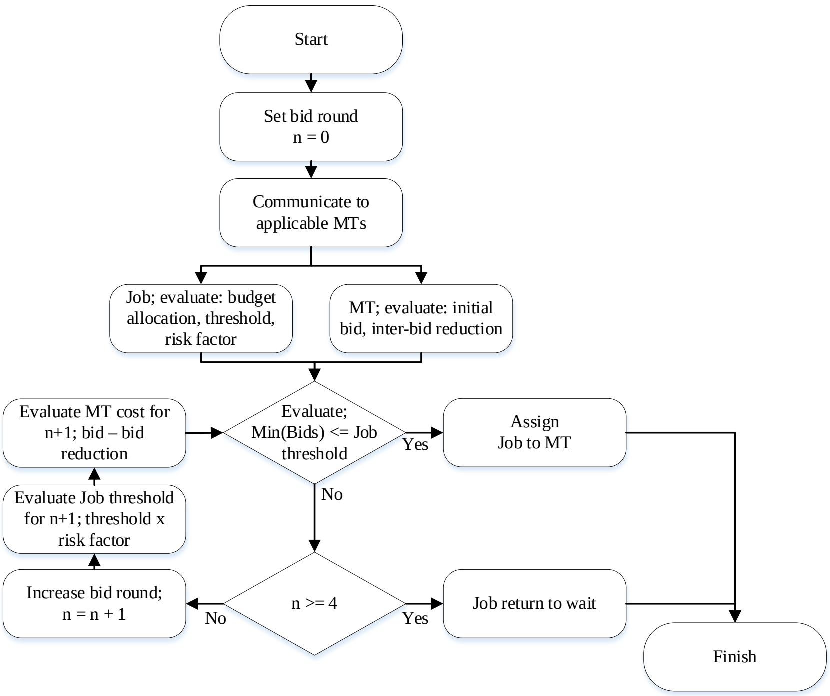

Figure 2 Job operation tendering process

A MT's bidding is calculated differently to Nassehi and Ma's Anarchic Manufacturing system, as it uses additional global information to forecast the near future beyond the immediate. On arrival to the system a job declares globally all capabilities required for its operations and MTs' declare their capabilities. A MT can calculate the expected queue length in the near future, by dividing the number of operations outstanding by the number of MTs for each relevant capability the MT has. A MT submits its bid based on current utilisation (recent past), its existing queue for the MT (immediate future) and the expected queue length based on the declared pool of operation capabilities required and other MTs (near future).

This Anarchic Manufacturing system is suitable for smart manufacturing and cloud based manufacturing as the distributed nature, business objectives and scale of both creates a very dynamic and complex planning and control problem. Smart manufacturing utilises intelligent resources that can self-organise and capture and process a vast amount of data. Anarchic Manufacturing is highly scalable and facilitates self-organisation through free market prioritisation. Centralised methods are unlikely to cope with the vast real-time data collection and analysis at a single point, especially if communication bandwidth is limited. CBM reflects a highly distributed free market structure, with many diverse and disparate participants; the Anarchic's free market structure allows a rapidly scalable and reconfigurable CBM system.

3. Traditional manufacturing systems

Traditional manufacturing systems have a centralised and often hierarchical structure, two systems, centralised and cellular hierarchical, are compared against Anarchic systems in this paper. CBM scheduling is highly dynamic and complex, although advanced centralised systems, e.g. search algorithms, can create optimal solutions, these often become ineffective at responding to disturbances in dynamic scheduling scenarios (Ouelhadj and Petrovic, 2009).

Dynamic centralised methods using heuristic dispatch rules, e.g. First In First Out (FIFO), are representative centralised methods. For both systems, the dispatch rule allocates a job to the next available capable machine or cell, as assessed by Work In Progress (WIP). The centralised system has a single coordinator that allocates a job to MTs according to its next operation. The hierarchical cellular system has a two-stage process: a new job is allocated to the cell with the lowest occupancy that can at least fulfil the job's next operation; within this cell the job is allocated to the next available and capable machine. On completing an operation, the job reports to the cell coordinator and is reallocated to a machine, or back up to the system coordinator one tier higher if the cell cannot fulfil its next operation. All three systems are directly comparable as there is no significantly advantageous information provided or significantly more sophisticated mechanisms used by any system.

4. Experimental framework

The experimental framework investigates the impact of mass customisation and scale in a cloud based manufacturing scenario, whilst minimising noise for clearer analysis. The overall experimental setup involves continuous job arrivals to maintain a holistic 50% MT utilisation. Each job has four sequential operations, the capabilities and durations of these are varied, see variable parameters below. Overall, there are eight operational capabilities (A-H) and the average operation duration is maintained throughout. MTs carry out one operation at a time and have two capabilities (e.g. capability C & D); they are located randomly in the modelling space. For all systems the MTs process jobs on a FIFO basis. On completing all operations, jobs leave via a central ship point. Only two parameters are varied, the degree of job operation customisation and system scale. Operation customisations are varied by duration and capability, parameter is denoted as α. For α = 1, homogenous jobs are produced with identical and precise durations and a sequential operational capability requirement (i.e. A-B-C-D or E-F-G-H); for α = 2 durations are random uniformly varied ±25%; for α = 3 durations are random uniformly varied ±50% and capability of each operation is random uniformly selected from all capabilities (A-H). For the second variable parameter scale, denoted as β, levels are: β = 1 40 MTs, β = 2 80 MTs, β = 3 800 MTs. Experiments were at all possible combined levels of α & β, each experiment was repeated for ten runs, each run kept the same random inputs. All experiments and systems were modelled using Agent Based Modelling on the AnyLogic platform. The metrics recorded were normalised WIP, this by MT i.e. average queue size; and waiting time, which is lead time less operational time (randomly varied) i.e. time for moving and queuing.

The systems operate as per Sections 2 & 3, whilst accommodating this experiment. For the hierarchical cellular structure, the number of cells maintain a rough average of ten MTs per cell; MTs are allocated to cells by their location's grid coordinates. The centralised system has a single coordinator and the Anarchic allows direct communication between MTs and jobs. Jobs consider the moving time in their tendering evaluation and slightly prefer closer MTs, but communication range is not restricted. Additionally, in the Anarchic system there is only one currency and all jobs are allocated the same budget which is the average expected operational cost for all operations.

5. Results and discussion

The experimental results were averaged for all runs and each combination of α & β, shown in Figures 3-4. At a high level, these metrics demonstrate that the centralised system remains consistent for all experiments, rather both the hierarchical and Anarchic improve with scale. The absolute superior performance of the Anarchic system is evident, as is the very poor hierarchical cellular system; which never reaches system stability, see Figure 3.

WIP / machine tool displays a clear trend of an improving Anarchic performance and the hierarchical cellular system is consistently poor. The centralised system retains a consistent performance, however, the Anarchic improves with scale. This is likely to be an emergent outcome of the Anarchic's free market architecture; as competition increases, overall efficiency does too. Increasing scale increases system complexity and difficulty to become allocatively efficient, the result that the Anarchic system improves with scale and therefore complexity, under certain scenarios, is very promising. The hierarchical cellular structure is clearly the worst to fulfil mass customisation, the restrictive architecture heavy detriments performance.

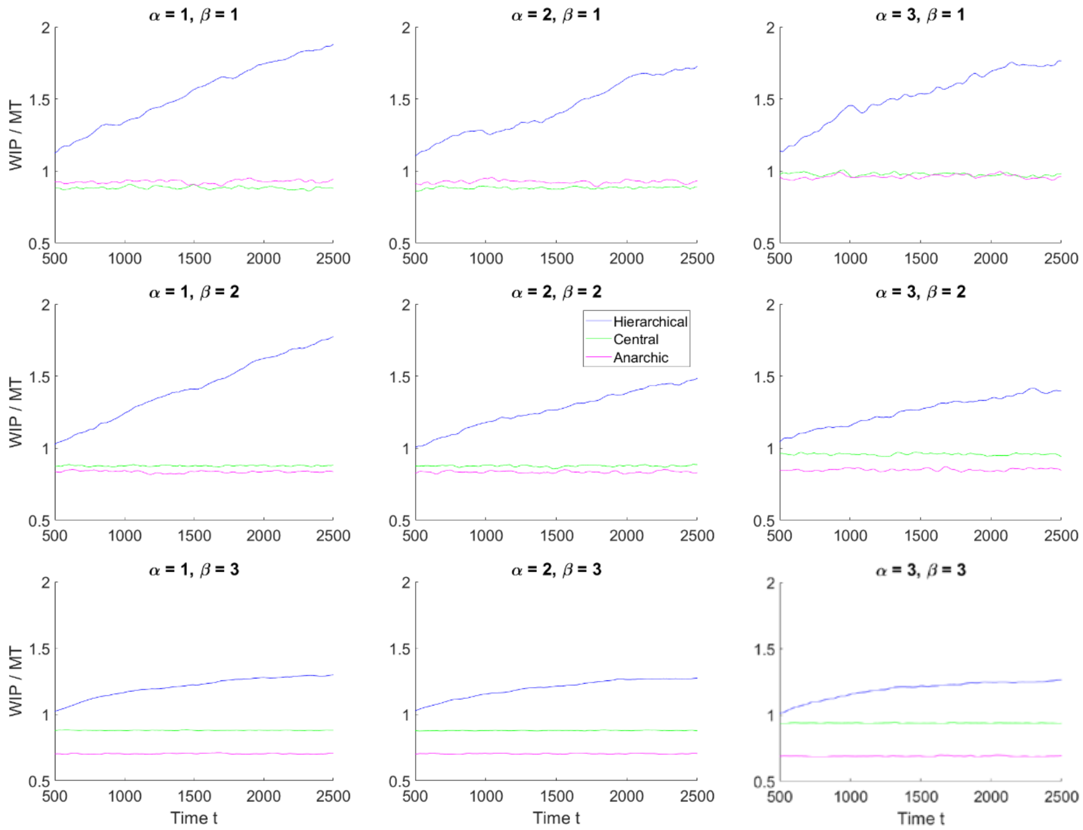

Figure 3 WIP / MT results

Waiting time results show a similar outcome, whereby the hierarchical system performs significantly worse, rather the centralised and Anarchic perform consistently; with the Anarchic being superior in large-scale scenarios (β = 3 at 800 MTs). Figure 4 displays these results, the outcomes are clear from the probability densities and the 90% of population mark. The consistency of performance for the centralised and Anarchic systems is positive, however, the hierarchical cellular structure's long tail is unacceptable for most manufacturing scenarios.

From these experiments it has been shown, under certain conditions, Anarchic systems perform best and improve as scale increases; all systems reacted similarly to increasing customisation. This outcome indicates that Anarchic systems may be best used for planning and control of smart manufacturing and CBM scenarios; it certainly warrants further investigation. Furthermore, contrary to traditional methods to deal with complexity, by creating hierarchical structures, a single centralised method or an Anarchic distributed system is better. Further levels of hierarchy and cell structures significantly impede overall performance; they will likely restrict flexibility and will not be able to manage the large complexity associated with mass customisation. Anarchic Manufacturing provides a novel approach to solving mass customisation through free market principles.

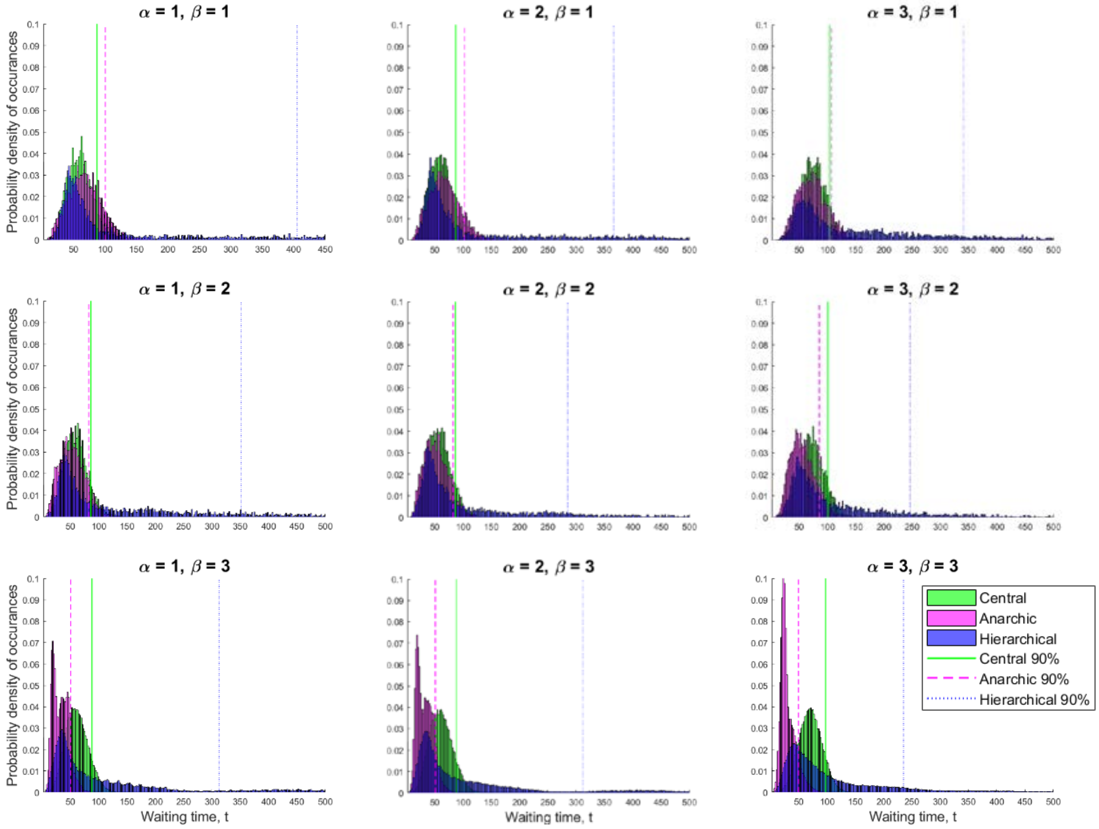

Figure 4 Waiting time results

6. Conclusion

Mass customisation is a smart manufacturing and cloud based manufacturing business objective, characterised by providing individually customisable products at mass production costs and lead times. For CBM and any significant networked manufacturing supply chain, scale is a significant complexity driver. This paper demonstrates, under certain scenarios; Anarchic systems improve as scale increases; hierarchical cellular structures are very poor under all scenarios and all systems can deal with increasing customisation well. Manufacturing management has traditionally managed complexity and scale through increasing levels of hierarchy, however this creates an overall poorer performance. Centralised structures may work well, but they have a single point of failure and must be able to deal with large-scale systems and have very strong infrastructure to gather data to a single point. Anarchic Manufacturing systems are highly scalable and can deal with complexity well; this warrants further investigation to realise the smart manufacturing and CBM vision.

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