CHARACTERIZATION OF MULTI-OBJECTIVE PERFORMANCE METRICS IN RELATION TO INVENTORY CONTROL STRATEGIES

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Abstract:

This paper presents experimental work conducted on a theoretical three-stage tandem production line to investigate the influences the control parameters, of various production control strategies, have on determining an optimal strategy to minimise inventory while simultaneously minimising backlogged demand. The production control strategies considered were Kanban, Minimal Blocking, Hybrid Kanban-CONWIP and Hybrid Minimal Blocking-CONWIP. Complete enumeration of the decision spaces within prescribed ranges for the control parameters revealed the importance and direction of influence of each control parameter for each strategy. These insights will be useful for designing computationally efficient multi-objective optimisation algorithms for this class of problem.

Keywords:

Pull type control strategies, Multi-objective evolutionary optimisation, Serial lines, Multi-stage production systems

1. INTRODUCTION

Production control strategies are intended to manage authorisation cards for parts entry into a system and the inherent semi-finished goods flow among workstations. Pull type control strategies frequently present superior performance in inventory level control and general effectiveness in the presence of stochastic demand [1-3]. Comparison studies of well-known pull type control strategies including: Kanban, Basestock, Hybrid Kanban-CONWIP have been conducted and presented in the literature previously [3-5]. Only a limited number of publications present multi-objective approaches in production and inventory control optimisation.

Andijani [6] developed a decision support framework using a simulation model combining the Analytic Hierarchy Process (AHP) technique to determine the Kanban allocations where the total number of Kanbans was assumed to be fixed. Three performance metrics were considered; namely mean WIP (Work in Process), mean flow time and mean throughput. AHP was used to identify the most-preferred Kanban combination among the non-dominated front. The same approach is found in another study [7] to compare Hybrid and Kanban control strategies. In the literature, there are studies that either implement a multi-objective genetic algorithm (MOGA) alone [4, 8] or integrate a multi-objective algorithm as part of their optimisation method in order to explore the experimental space and locate the optimal solution set

[9,10]. The Strength Pareto Evolutionary Algorithm 2 (SPEA2) was used in [11] to compare Kanban, Basestock, CONWIP and Hybrid Kanban-CONWIP control strategies under two different manufacturing loads (light and heavy load) and two types of variances in machine processing time (high and low variance). WIP and Service Level were the performance metrics used in research works presented in [9,10]. Onyeocha, C.E, et al. [9] compared the performances of two production control strategies in multi-product manufacturing environments, namely Hybrid Kanban-CONWIP and Hybrid Basestock Kanban CONWIP (BK-CONWIP). Smew, et al. [9] compared the performances of simulation based optimisation using a MOGA with a Gaussian Process Metamodel optimised using the Desirability Function Approach to generate the Pareto front for a supply chain implementation of the Hybrid Kanban-CONWIP strategy. A MOGA was integrated with a regression model in [10] to improve the efficiency of the optimisation approach. The regression model was trained by using design of experiments and response surface methodology. During the MOGA optimisation process, regressions are integrated to maximise throughput and minimise WIP simultaneously.

None of this prior work has presented a complete enumeration of the decision space to provide evidence that the optimisation processes used found the true Pareto Front. The objective of this work is to explore the characterisation of the performance spread and investigate the impact on performance metrics as a result of changes in the number and distribution of production authorisation cards within a single product, multi-stage tandem production line. Full numeric simulation results for four pull type control strategies (Kanban, Minimal Blocking, Hybrid Kanban-CONWIP and Hybrid Minimal Block-CONWIP) are examined using the upper and lower Pareto fronts, the performance impact and the spread characteristics relative to the different control strategies. The goal for the MOGA is to address the trade-offs between average WIP and average backorder queue length.

Section 2 of this paper provides a brief overview of the production control strategies examined in this research. Section 3 provides details on the experimental procedure and the results of the experiments are presented and discussed in Section 4. Finally, Section 5 of this paper provides conclusions and directions for future work.

1.1. Pull type production line strategy

The primary objective of a pull control strategy is to improve a production system though inventory reduction by implementing a production control and work coordination mechanism reacting to actual demand rather than forecasted demand. This study uses multi-stage serial production lines for the simulation cases. Production lines in this study are subdivided into workstations consisting of a machine and buffers. The following section briefly explains the material flow and control strategies under investigation.

1.1.1. Kanban

Kanban control was originally developed in the Toyota production system to reduce and eliminate waste related to humans and resources [12]. Kanban systems have one buffer placed between two machines functioning as both the output buffer of the upstream station and the input buffer for the downstream station. When specific amounts of items stored in the finished goods buffer at the end of the production line are consumed to satisfy an order, the Kanban card detaches from the products, it flows back upstream and authorises the same amount of items to enter into the workstation to conduct its production activities. The detailed control mechanism is represented in Figure 1.

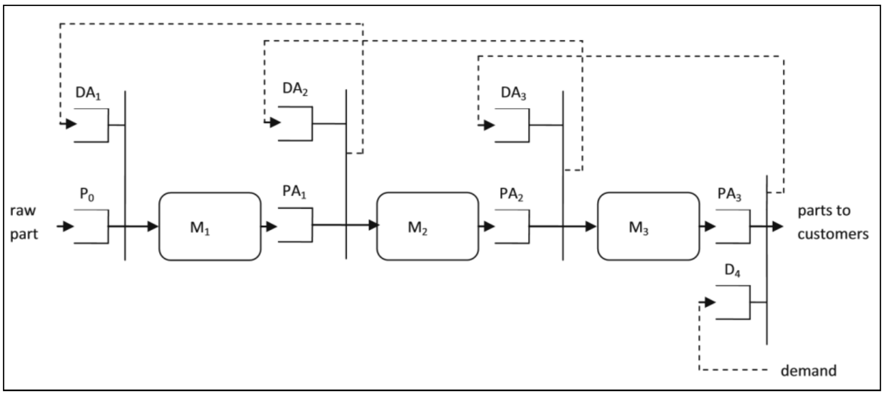

Figure 1 –A three stage Kanban system [4]

1.1.2. Hybrid Kanban-CONWIP

The Hybrid Kanban-CONWIP is a control strategy that combines Kanban and CONWIP, firstly proposed by Bonvik, et al. [3]. CONWIP in this hybrid strategy controls the overall number of WIP though the whole production line. Every production stage except the last one uses Kanban to control the inventory level to provide local (workstation) WIP control. The inventory of last stage is not controlled by any parameter and uses a push type control mechanism. The detailed control mechanism is represented in Figure 2.

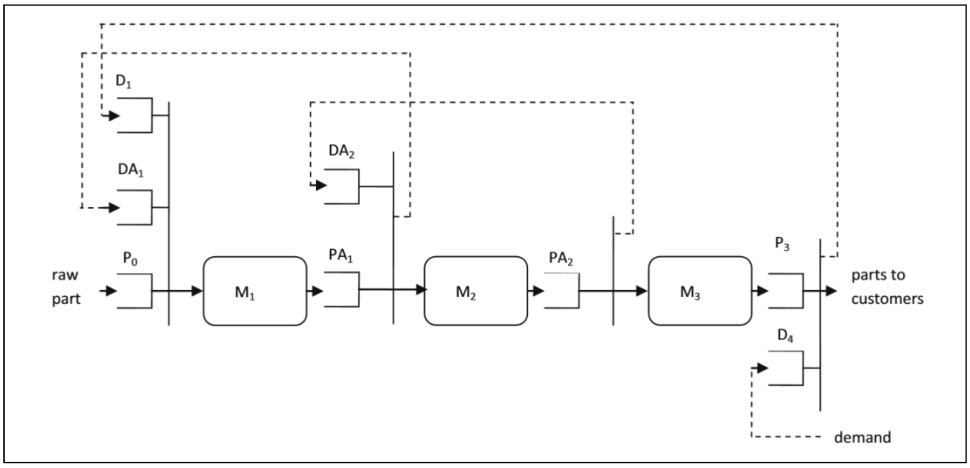

Figure 2 – A three stage Hybrid Kanban-CONWIP system [4]

1.1.3. Minimal Blocking

The logistics of material flow and authorisation cards for the Minimal Blocking and the Hybrid Minimal Blocking-CONWIP strategy are quite similar to the Kanban and Hybrid Kanban-COWNIP control strategies, respectively. The only difference between them is that each workstation consists of two buffers, an input buffer and an output buffer. Parts in a tandem Minimal Blocking model will be transferred to the downstream input buffer and the flow of parts downstream will not get blocked if the upstream station finishes the processing task before the downstream station becomes available provided that there are free Kanban cards at

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the downstream workstation [13]. The parts will simply move from the upstream workstation's output buffer to the downstream workstation's input buffer.

2. EXPERIMENTAL PROCEDURE

ExtendSim was used to develop a simulation model of a three-stage tandem production line, to which the different production control strategies were applied. The simulation models in this experiment are adapted based on the one used in [3,4] and validated by comparing results from the simulation models and the data in the literature [3]. This system produces a single product with three workstations where each workstation consisted of a machine and an output buffer. The production is necessarily passed through each workstation sequentially before it reaches the finished goods buffer. Product demand to the system follows an exponential distribution with mean of 1.01 min. Job size is set at 1, with no lead time. Therefore, an order will be satisfied immediately when there is a part available in the finished goods buffer, otherwise the demand is marked as backordered and stored in the backlog queue which uses a Fist Come First Served discipline. The queue for backordered demand has an infinite capacity. The processing time for each machine follows a lognormal distribution and is set to represent a high load situation where the mean processing time (mean = 0.71 min and standard deviation = 0.02 min) is slightly smaller than the mean order arrival time. Workstation 2 is assumed to be the bottleneck of the entire system which has a longer processing time than the other two workstations which is also modelled with a lognormal distribution (mean = 0.96 min and deviation = 0.02 min). All machines in the system have the same exponentially distributed mean time between failure time (mean = 1000 min) and exponentially distributed mean time to repair (mean = 3 min) for considerations of unexpected production disruption. The four pull-type control strategies are submitted for comparison in this experiment. The limit of parameters setting is confirmed by simulating them at two extreme conditions where all the authorisation cards are at lower or upper limits. The results indicated that enough exploration could be set by using the settings presented in Table 1.

Table 1 – Authorisation cards configuration

Strategy	Number of Kanban (for each workstation)	CONWIP
Kanban	1 to 20	-
HK-CONWIP	1 to 20	1 to 60
Minimal Blocking Kanban	1 to 20	-
Hybrid Minimal Blocking-CONWIP	1 to 20	1 to 60

The following are the simulation modelling assumptions for all strategies under investigation in this study:

1. No delay in transiting materials between workstations, Kanban cards communication is immediate.
2. All buffers in the system follow the first in first out rule and machines follow the first come first served policy.
3. Before a product enters a workstation, it needs to wait for an available authorisation card.
4. Any demand not satisfied will wait in a queue at the final production stage until matched by the finished good supply. The backordered demand will not stop demand creation, but will be satisfied before any newly created demands can be satisfied.

The simulation termination condition was that 100,000 orders are satisfied. There are in total 8,000 cases that needed to be executed for both Kanban and Minimal Blocking, and 24,000 cases for both of the hybrid strategies. This allows for the creation and exploration of the real Pareto front and the matrix spread type. Performances of all these cases are evaluated from simulation models at a single run as in the paper written by Xanthopoulos and Koulouriotis [4], each scenario in the space is simulated long enough to exclude the impact of the warm up period.

3. RESULTS AND DISCUSSION

The entire experimental space for the four control strategies was analysed thoroughly. Performance results for Minimal Blocking strategies data is plotted in Figures 3 & 4, detailing the output spread:

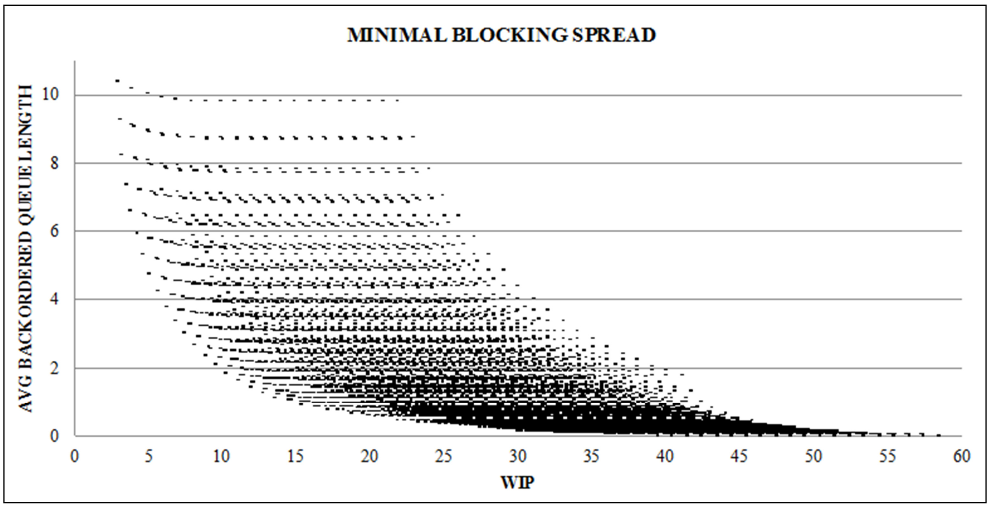

Figure 3 – Minimal Blocking Strategy – Performance Spread

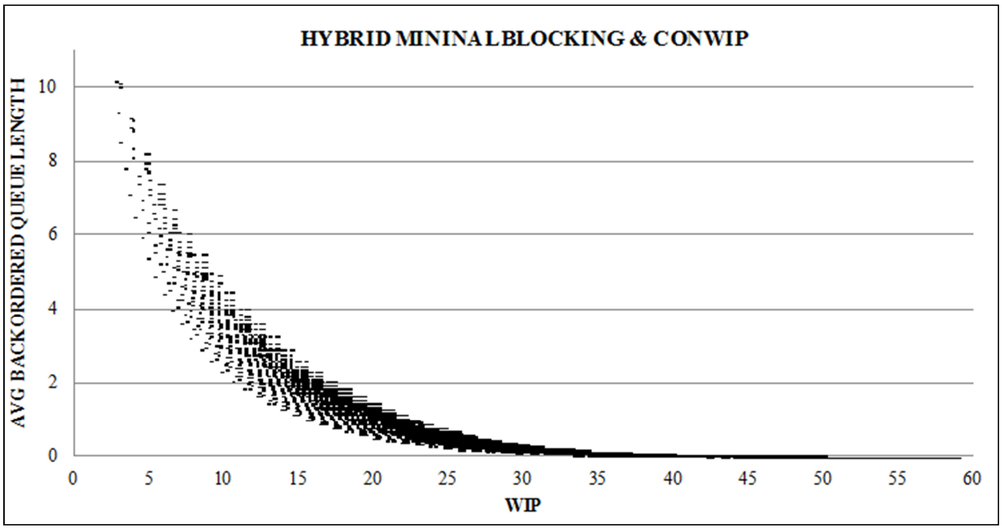

Figure 4 – Hybrid Minimal Blocking-CONWIP Strategy – Performance Spread

From the above figures, it is possible to verify the overall nature of the performance points spread. It is found that the tested hybrid strategies consistently perform better with significantly lower variability and spread in relation to any other control strategy in the study.

Kanban and Minimal Blocking control strategies present a broad spread between the lower (optimum) and upper (worst case) performance limits. The performance points of the hybrid control strategies have a higher density and are more evenly spread. The upper and lower Pareto fronts describe in detail the system performance as depicted in Figure 5 below.

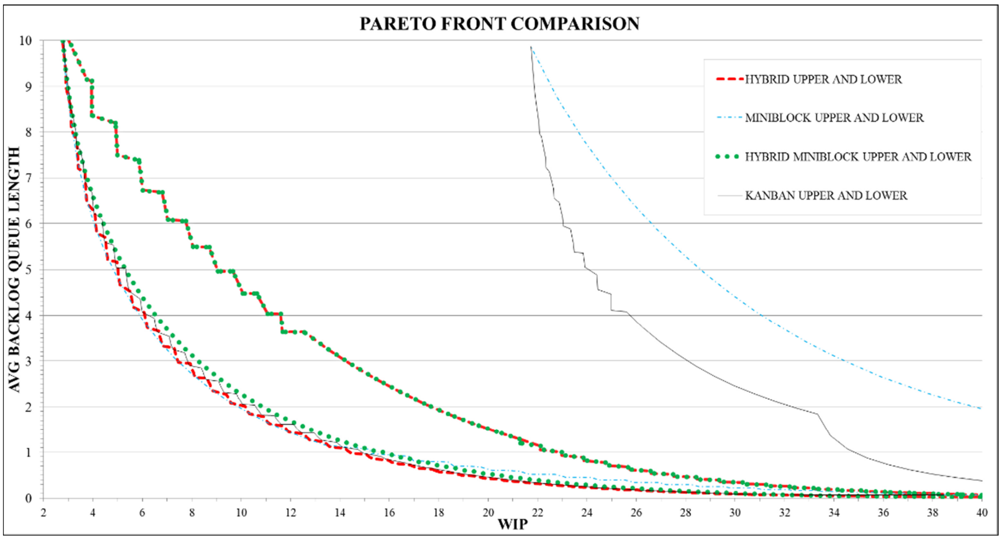

Figure 5 – Multiple Strategies Pareto Front Comparison

From Figure 5, it can be observed that:

1. When the decision maker has a preference for maintaining WIP at low values and is willing to accept higher backorder levels, Minimal Blocking Kanban performs as good as and often better than Hybrid Kanban-CONWIP. Additionally, Hybrid Minimal Blocking-CONWIP is the worst performer and Kanban is somewhere between Hybrid Kanban-CONWIP and Hybrid Minimal Blocking-CONWIP.
2. As the decision maker places more emphasis on minimizing the backlog (below 1 unit) Minimal Blocking Kanban becomes the worst performer and Hybrid Kanban-CONWIP the best performer, while Kanban is still better than Hybrid Minimal Blocking-CONWIP in terms of WIP required to achieve the desired backlog level
3. As the decision maker approaches requiring a strategy that will deliver a zero backlog level the Hybrid Minimal Blocking-CONWIP begins to outperform Kanban.
4. Both Kanban and the Minimal Blocking Kanban have significantly higher upper Pareto fronts than the two hybrid strategies.

From a multi-objective optimisation algorithm deployment perspective, the Hybrid Minimal Blocking-CONWIP strategy and, in particular, the Hybrid Kanban-CONWIP strategy would prove to yield significantly higher computational efficiency than Kanban and Minimal Blocking Kanban strategies. In some specific cases, the real Pareto front can be unknown due to the size of the experimental space. So, the Pareto front formulated by a multi-object optimisation algorithm could be a line between the upper fronts and lower fronts presented in the abovementioned figures. Both hybrid strategies in this study have the smallest area between the real upper and lower Pareto fronts. Therefore, there is a greater likelihood of obtaining a point near to the optimum Pareto front without the need to explore the entire combination along a large experimental space.

In order to investigate the impact of each of the types of authorisation cards on the performance metrics, Figures 6–8 present the impact of each card type in the Hybrid Kanban-CONWIP strategy and Figures 9–11 present the impact in the Kanban strategy.

In the Hybrid Kanban-CONWIP strategy, from Figure 6, it can be seen that for this system where the bottleneck is located at the second workstation maintaining the Kanban allocation to workstation 1 (Kanban1) as low as possible will minimize WIP. Additionally, from Figure 8, it can be seen that increasing the CONWIP level is necessary to minimize the backorder buffer size. Finally, from Figure 7, it can be seen that the Kanban allocation to workstation 2 (Kanban2) has no discernible impact on the performance metrics. That is to say that the lower Pareto front can be found by controlling the allocation of Kanban cards to workstation 1 and the number of CONWIP cards in the system, the number of Kanbans allocated to the second workstation is irrespective. A similar set of observations were drawn from investigating the Hybrid Minimal Blocking-CONWIP strategy.

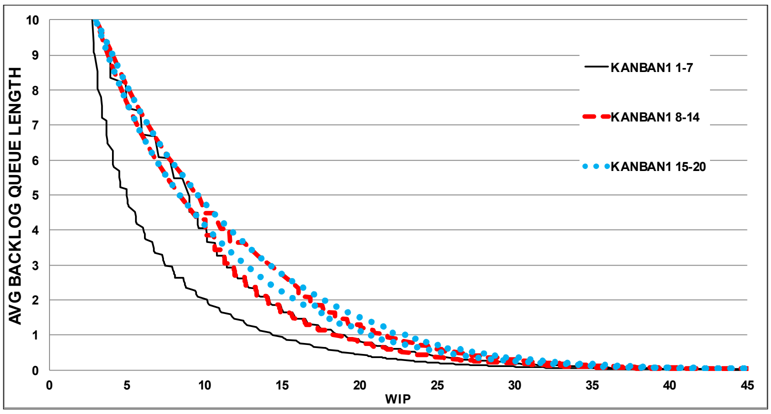

Figure 6 – Hybrid Kanban-CONWIP control strategy – Kanban 1 performance impact

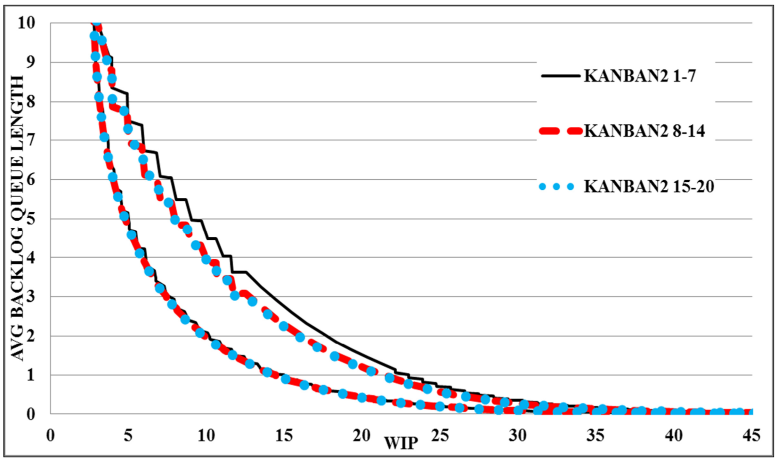

Figure 7 – Hybrid Kanban-CONWIP control strategy – Kanban 2 performance impact

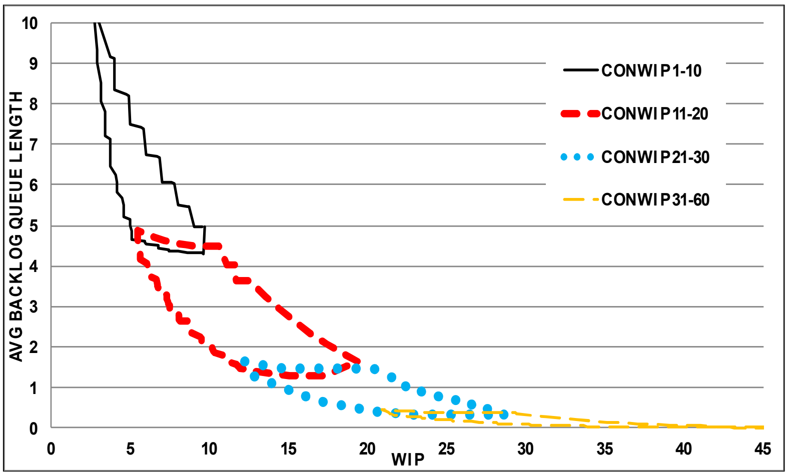

Figure 8 – Hybrid Kanban-CONWIP control strategy – CONWIP performance impact

Similar to the hybrid strategies, the importance of precise control of authorisation cards at Workstation 1 (Kanban1) is very significant for achieving high performance in terms of minimizing the WIP required to achieve a desired backorder level in the Kanban strategy (see Figure 9). The backorder level is most influenced by the combined settings for the Kanbans allocated to Workstations 2 & 3 (Kanban2 & Kanban3). As can be seen from Figures 10 & 11, if the decision maker requires low backorder levels then it is important to simultaneously set both Kanban2 & Kanban3 at high levels. Setting one lower could significantly degrade performance in terms of backorder level. A similar set of observations were drawn from investigating the Minimal Blocking strategy.

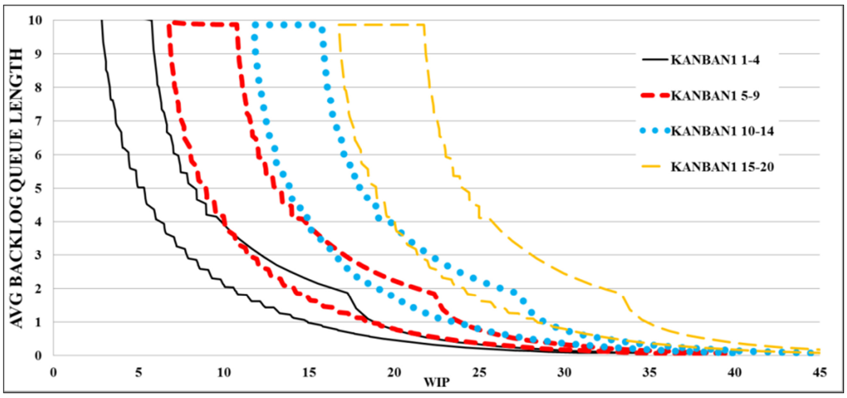

Figure 9 – Kanban control strategy – Kanban 1 performance impact

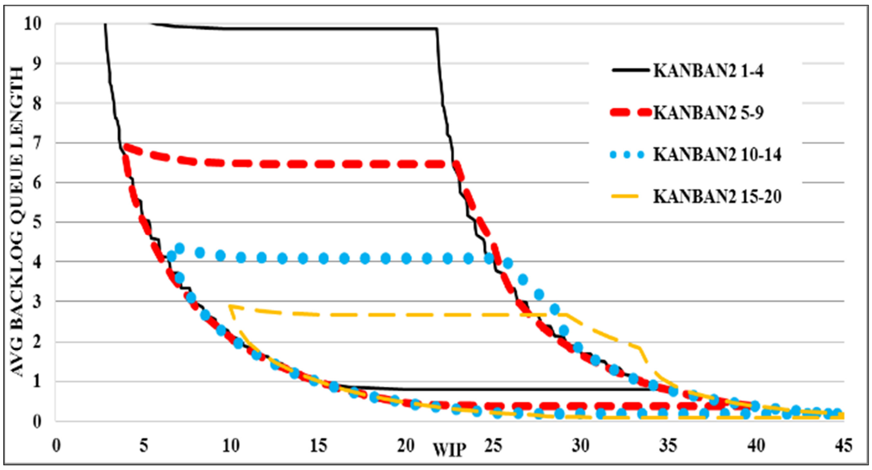

Figure 10 – Kanban control strategy – Kanban 2 performance impact

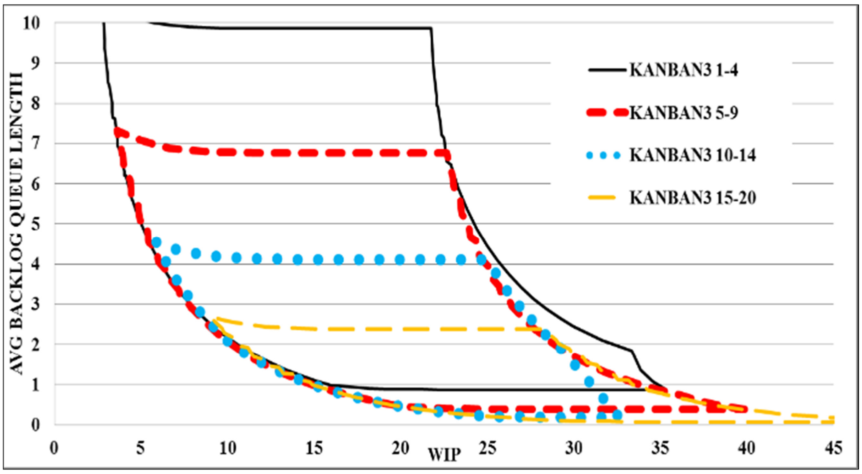

Figure 11 – Kanban control strategy – Kanban 3 performance impact

4. CONCLUSIONS AND FUTURE WORK

A number of observations of the influences of the control parameters (types of authorisation cards) have been drawn from examining the solutions in the experimental space. These observations may be useful for improving the efficiency of multi-objective genetic algorithms for investigating and optimising pull control strategies. For example, we are currently investigating how these insights might prove useful in the selection of Crossover and Mutation operations in a Multi-Objective Genetic Algorithm (MOGA) to minimise the computational effort required to derive the optimum (lower) Pareto front. For parameters that are have been demonstrated to be most influential in minimising WIP for a desired backlog level (Kanban1 in all cases examined here) it would be important to ensure that optimisation algorithm is able to create offspring with a high level of variance in this region of the chromosome, to avoid being trapped in a local optimum. Whereas, for parameters that have been shown to have the most influence of the backorder level (Kanban2 and Kanban3 in the Kanban control strategy and CONWIP cards in the Hybrid Kanban-CONWIP control strategies) it may be important to ensure that the optimisation algorithm generates offspring which are similar to each other in these sections of the chromosome. All remaining parameters could be maintained at predetermined levels, thus reducing the overall experimental search space. Further experimental work to characterise the impact of the bottleneck location and severity on the influences and importance of particular control parameters for each strategy is also required. This can be achieved by extending this analysis to longer lines.

5. ACKNOWLEDGMENTS

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