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Conflict and error management: A case in the furniture industry

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CONFLICT AND ERROR MANAGEMENT: A CASE IN THE FURNITURE INDUSTRY

A Thesis

Submitted to the Faculty

of

Purdue University

by

Glenn Candranegara

In Partial Fulfillment of the

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of

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To my family,

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ABSTRACT

Candranegara, Glenn. M.S.I.E., Purdue University, May 2015. Conflict and Error Management: A Case in Furniture Industry. Major Professor: Shimon Y. Nof.

The purpose of this study is to investigate and provide tools for the furniture industry, for detecting and preventing damage from propagating errors. Many of the errors cascading in a furniture manufacturing facility are typically detected only after the original process that causes the error had already caused errors. Previous research has developed and validated theoretical methods, such as CEPD, to prevent and detect errors and conflicts. This thesis is the first effort to implement the logic of CEPD in the furniture industry. There are four relevant measures that are analyzed and improved in this thesis; they are preventability, reliability, damage, and time to completion. The study proposed an Efficient inspection assigning method that is based on Centralized and Decentralized strategy. The efficient inspection method increases performance by reducing the working time and maintains the preventability and reliability of the system. The method was validated for a case of laminating department of a furniture industry. A total of eighteen scenarios for the case were analyzed and simulated using ARENA simulation. For comparison, each simulation result scenario went through pairwise t-test. The significance test shows the new Efficient inspection method can maintain preventability and reliability with lower working time: On average, reliability was increased by 0.54% with standard deviation 0.09%; working time was reduced on averaged by 5.54% with

standard deviation of 2.13%. Both improvements are directly realized by error and conflict prevention. Future research will address hybrid decentralized/centralized system optimization on performance without deteriorating reliability. Useful observations were also found that can lead to improvements in the CEPD logic.

CHAPTER 1. INTRODUCTION

1.1 Introduction to Conflict and Error

Conflict and error (CE) have been an issue throughout the age of production systems. The definition of an error is any input, output, or result that does not meet the requirement or expectation from a system (Klein 1997). A conflict is an irregular result between sharing resources' tasks, goals, or plans. It occurs when there is a deviation between two or more collaborating units in a system (Chen and Nof 2010). There is a strong need to detect, diagnose, and prevent CE as many studies in manufacturing control systems try to achieve zero defects (Lee 1995, Shigeo 1989, and Venkatasubramanian 2003). In practice, CE manifests everyday and the need to prevent and/or recover from the undesirable event makes it necessary for having a robust system.

Most of the studies work on the theories but they need depth on real data usage as well as the constraints within the production system, especially when using workers/humans as one of the simple resources (Baines *et al*. 2004). This paper addresses the issue on humans as a resource in simulation and the validation challenges that occur when the validation depends on the external human performance model. Later the effect on humans as the link in manufacturing simulation will reflect in the transportation tools in the model as it depends on humans.

Early error detection has been studied in various kinds of system segments and it is proven that during the earliest stage of product/service production, the value for having error detection and prevention results in lower cost and faster recovery. This applies to any engineering problem regarding product/service development across all segments. In order to detect CE instantaneously, certain tools have to be integrated into the system so it recognizes the exceptions automatically. After it detects, it has to diagnose and do prognostic action for protection against repeating the same error (Chen and Nof 2007). At the starting point, the tools have to be based on an algorithm that is generic so they are flexible towards various segments and they have to meet the demand of their user.

There are extensive studies that have developed methods and algorithms to detect, diagnose, and prevent CE. Constraint-based conflict and error prevention and detection (CEPD) algorithms have been found to be more general (Chen and Nof 2007, 2012a) for different networks. Collaboration control theory using agents is one of the potent ways to induce error detection and prevention (Chen and Nof 2010). There is still handful amount of study about the inspection network (Chen and Nof 2007) and resource allocation that depends on performance, reliability, and error (Moghaddam and Nof 2014). Another aspect of the research problem is that none of these promising methods has been investigated for its usefulness in the furniture industry.

1.2 Research Objective

While the theory of CEPD has been validated, it has not yet been implemented and tested in an existing production or supply system. In this thesis, a model based on the theoretical CEDP algorithm was developed and applied in a furniture-manufacturing firm

(FMF) facility to study the advantages and disadvantages of the model. There are modifications needed in order to synchronize and apply the existing system in the FMF facility, they are:

- Implement constraints and CE dependence
- CE database
- Product requirement complexity
- Sequential and parallelism categorization on production line inspection station
- Integrating with existing traditional prevention and detection methodology.

The objective of this research is to apply the developed centralized and decentralized CEPD algorithm into existing FMF's system and modify the algorithm to adapt into the existing industrial system. Using the data collected, the study analyzes and simulates six different CE inspection stations assignments and provides result comparison from those different strategies simulation results. The results can help decision makers (DM) to assign quality control (QC) agents on specific inspection stations in order to optimize their workload. The simulation model is separated into two inspecting methods: one-by-one and batched. The inspection assignment strategies are: inspection in all process (Decentralized); inspection in buffer (Centralized); and inspection in efficient assigning station using binary variable function that is based on historical error data probability. The importance of trade-off between reliability, cost, and performance (Chen and Yen 1995) shows that dynamic checking interval should be deeply investigated. Using efficient assigning inspection station based on failure rate helps the system performance in time and cost. The efficient assigning model increases the system performance by having a Centralized inspection completion time and Decentralized reliability and preventability. Different number of QC resources is also compared to ensure reliability performance is stable with lower resources, in order to have efficient yet effective inspection. For validity purposes, the mean differences for 100 replications between scenarios were compared using paired *t*-test. The significance for different number of QC agent helps DM calculate the trade-off between cost, time, preventability, and reliability.

1.3 Research Contribution

The presence of CE is highly undesirable for any kind of work. In order to have a resilient system, CE detection and prognostics process is necessary. The distribution for detection and recovery work has to be balanced to sustain desired level on the system's performance and reliability (Chen and Yen 1995). The proposed distribution network, which is the efficient inspection distribution, for this study inspired by centralized and decentralized CEDP network (Chen and Nof 2007). This study compared the significance on reducing fully decentralized inspection process with the reduced station based on the time and cost. This study also contributes on evaluating the CEDP algorithm implementation in furniture industry.

The performance is studied using ARENA simulation resembles the situation in a furniture lamination department. There are four metrics compared to justify the increase of performance from the proposed inspection network. The proposed network will be implemented in the facility to increase reliability and performance. Having both batching and one-by-one inspection method gives the assumption as having QC human agent and QC robot or sensor, respectively.

1.4 Thesis Structure

The remainder of this thesis is organized as follows. Section 2 describes the background for the research. Section 3 describes the methodology to create the model and simulate for comparisons. Section 4 describes the simulation model used and the validity test by checking the difference significance. Section 5 describes the simulation outcome and validation test result evaluation. Section 6 describes the conclusion and possible future research work.

CHAPTER 2. BACKGROUND

2.1 Introduction

The background section describes the research foundation for the CE management for this study. Models and tools from other works inspire this study in reliability and performance trade-off, CE on different networks, and resource allocation administration. Previous studies that devoted on error detection and prevention include agent-based error prevention algorithms (AEPAs) in sequential production/service line (Chen and Nof, 2012a), multi-agent diagnosis for global diagnosis in large distributed systems (Roos, ten Teije, and Witteveen, 2003), CE detection active protocol and agent deployment for shipping/distribution environment (Yang, Chen, and Nof, 2005), and constraint based CE detection and prevention for general CE management (Chen and Nof, 2010).

2.2 Collaborative control theory for e-Work, e-Production and e-Service.

Productions are emerging to change of its fundamentals and the concern is the effectiveness of design and implementation of the e-System. Studies on e-Work applications (Nof, 2005, 2006a) that covers multi agent interaction, sensors and its networks, security, productivity management and collaboration between enterprises manages to explain the differences of e-X and X, and how these applications form and integrate with existing principles that make the foundation of e-Work.

There are six principles of collaborative control theory defined with the purpose of increasing the effectiveness of work and enabling organizations to achieve their goals (Nof, 2007 article on CCT in ARC).

1. Cooperation Requirement Planning (CRP) is defined into two stages: CRP-I, advanced planning before execution and CRP-II, revise planning in real time to adapt with constraints. An effective e-Work requires advanced planning and adaptive planning.
2. Collaborative e-Work parallelism (CEP) is to make work activities be widely distributed instead of doing sequential (linear) work. The distribution includes location wise and interaction wise (human-human, human-robot, robot-robot).
3. Keep it simple, system! (KISS) focusing the simple system for e-Worker to minimize human error and delay. Computer communication system can be complex as long as it can work autonomously.
    a. Distributed planning of integrated execution method (DPIEM) correlates with determining optimal Degree of Parallelism.
    b. Conflict resolution in collaborative e-Work addresses the cost of resolving conflicts among e-Workers. Past research shown more autonomous detection functions is proven to make e-Work systems be effective and conflict scalable.
4. Collaborative fault-tolerance principle means that a team of weak robots or sensors has more effective result than a single faultless agent. The synergy of collaborative e-Work requires effective conflicts and errors handling.

5. Join/leave/remain (JLR) principle in collaborative organization is associated with the nature of enterprise that is working virtually and dynamically. The JLR describes the necessity of individual parties or organization to join or leave or remain the collaborative-networked ecosystem. The system has to measure the benefit and cost for the entity to remain inside the collaborative network. Analyze on multi-phase, creation, activity, dissolution and support. Multi-level (sub and/or multi) and multi-phase on the CNO.
6. Emergent line of collaboration and command (LOCC) is a principle of decision making formally and/or informally within and between organization with the question of who to contact and what channel to use and the format of messaging.

Network model resembles neurons with simpler vertex and channel. At multi level of implementation, the important features of the emerging production and service are the networks of the participating organization and collaborative teams. The direction and activity of the network model is flexible. Integrate network model to reach closer with neurons capability in information, collaboration and speed would make an efficient network as a whole. Bio-inspired network models imply that the network model for collaborative control stated before has similar design with human neurology system. More study needed to carry out how biological collaborative control works in order to increase the understanding optimization for e-Production and e-Service.

Bio-inspired design and collaborative control principles implies the design of collaborative control in e-Production and e-Service is inspired by biological control. There are two categorization of learning mechanism: centralized learning and decentralized (interactive) learning. The example given is the ant colony communication overcome overload interaction and this inspired how collaborative systems developed.

Collaborative e-Work is the advanced way to collaborate by using higher technology and autonomous system to improve e-Service and e-Production. Collaborative e-Work is changing our ways of thinking to improve e-Production and e-Service. Communication integration through computer science and technology is making advance collaborative control possible. To reiterate the collaborative network control is vital in both autonomous and non-autonomous working environment.

2.3 Constraint-based CE management

To make generic methodology applicable in different type of areas, constraint-based CE management is well suited (Chen and Nof 2012c). The detection approach in this paper compares three different approaches and they are: traditional, centralized, and decentralized method. Centralized and decentralized approach is different from traditional algorithm where they have relationship between constraints and they update constraint conditions automatically into the system for prognostics purposes. Traditional algorithm lacks diagnosis and prognostics as it creates less awareness for system robustness and does not support parallel production system.

Constraints in the CEPD can represent the states or conditions to determine if a component is faulty or not and the constraints shows the components' relationship. The relationship between constraints is comprised of a constraint network with nodes and links that represent the constraint and relationship, respectively. The constraint relationship has two types of links, inclusive and exclusive, where inclusive links have one-way direction and two-way direction link; and exclusive link does not have direction.

The links illustrate the network dependability to perform detection, diagnosis, and prevention of CE like in Fig. 1 and Fig. 2.

Centralized algorithm is created for sequential production/service line system. Fig. 1 is the logic flow for the centralized algorithm and each logic process on the link characteristics marks a different type of CEPD part. These three different parts are the detection, diagnosis, and prevention with dashed and dashed/dot lines separating each part. The logic of the algorithm follows a first-in-first-out (FIFO) queue for execution and it starts from oldest task if there is a queue. If there is no task in the queue, the centralized algorithm goes towards the detection part.

The detection part is responsible on finding constraints that are not satisfied before or during the current time and mark it as a CE. The constraint relationship is checked to ensure whether the constraint have link with other constraint and mark or unmark based on condition or state. After detection, the algorithm goes through the diagnosis part when CE is detected and it checks causes of CEs detected in the detection part. With all the potential causes of the CE, the algorithm moves to prognostics part. Prognostics have similar reasoning with diagnosis but the main difference is when constraint is related with future constraint that has not been occurred, the prognostic gives check mark. After that, the algorithm moves back to the FIFO tasks queue.

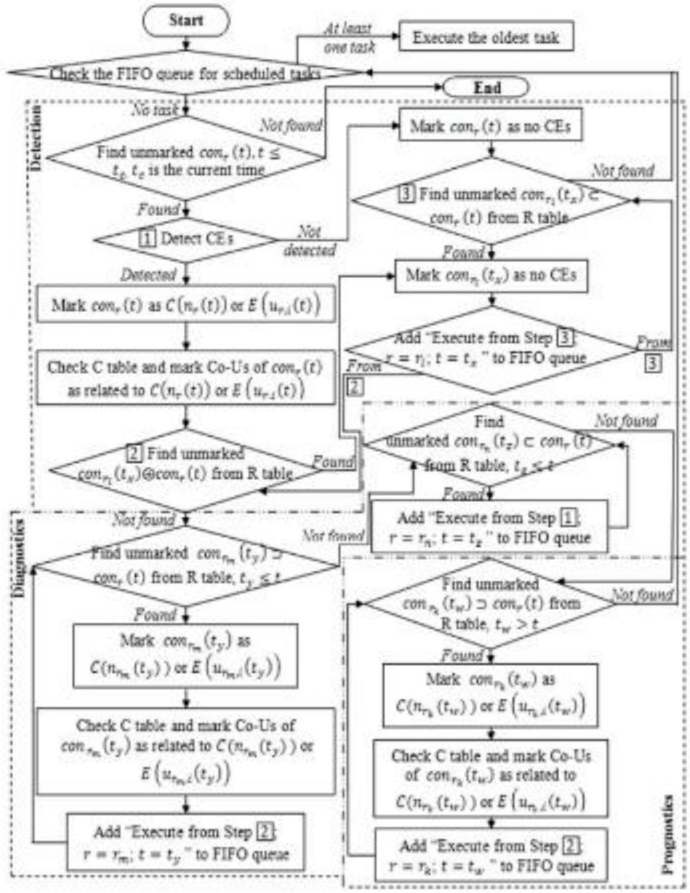

Figure 2.1 Centralized CEPD Algorithm Logic Flow (Chen & Nof, 2012c)

The advantage on putting constraint relationship modeling and utilization between each other enables the algorithm to diagnose and prevent the error faster than traditional algorithm. The disadvantage of having centralized algorithm is the abundant size data on the constraint-requirement table and relationship table, insignificant coverage area, and small effect on mean total CE damage. Decentralized algorithm, however, have better performances compared with other two algorithm.

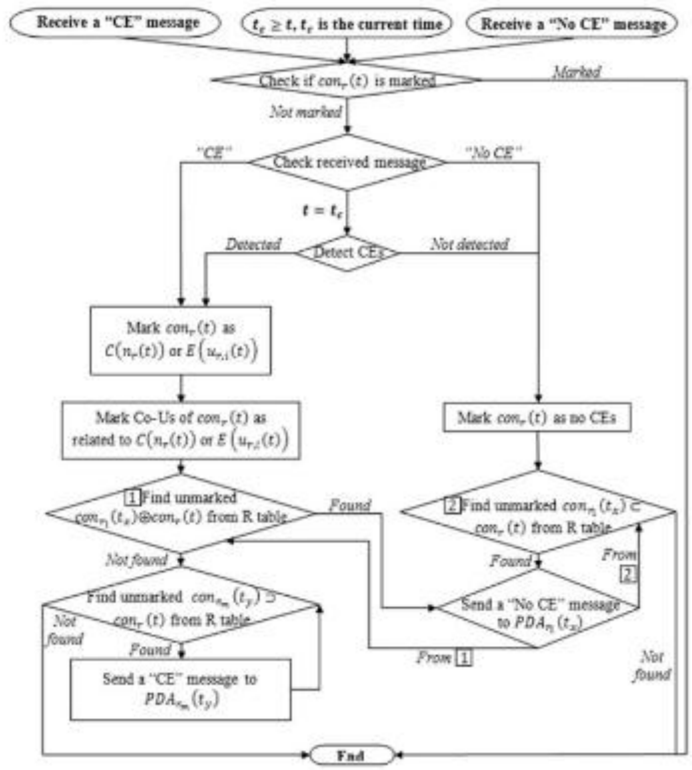

Figure 2.2 Decentralized CEPD Algorithm Using PDA (Chen & Nof, 2012c)

Decentralized algorithms are more focused on distributed prevention and detection methodology. The methodologies are more focused over parallel different networks. This algorithm uses intelligent prevention and detection agent (PDA) to execute the CE management methodology. The decentralized algorithm is less complex than centralized algorithm due to having collaborative PDAs performs the prognostics and diagnostics. For independent constraint, a PDA does not need a relationship (R) table. The decentralized algorithm, however, has limited coverage ability on sequential production/service line as it forms a linear relationship. There was a study regarding basic decentralized algorithm for sequential production/service line, however it has not been studied to apply using non-autonomous agents (Chen and Nof 2010).

The conclusion made from the paper is that the best methodology is decentralized algorithm where the agents detect, diagnose, and prevent errors by communication among them. When communication is not applicable between agents, centralized algorithm is recommended because the result is much better than traditional algorithm.

2.4 The effect of enhancing reliability towards performance

In this particular paper (Chen and Yen 1995), using periodic error checking algorithm tests storage system reliability but the issue is that the performance trade-off with reliability has not been discussed. Due to extra processing time, the system performance is degraded when excessive error checking is performed. There are many research efforts have been done in the area of performance evaluation of periodic data maintenance algorithm for optimizing service rate (Chen and Banawan 1992; 1993) but no performance analysis for fault-tolerant systems. The concept here can be used for any system that requires error checking periodically.

The paper develops a Markov model that helps determine error checking/recovery procedure executions. The goal is to maximize the number of cumulative requests without failure over a certain mission time or with maximized reliability and get the least requirement number of requests. The paper use probabilities error checking term in the form of periodic error checking, for example $q = 1$ means lowest interval between checking or performs error checking per access and $q = 0$ means no error checking capability. The parameter to represent the system's condition is $c(t)$ throughput the system at time t and conditioned being alive at time t. The reliability is the opposite state of the probability when the system is in fail state $Pr_f(t)$ at time t. In this equation, the first term represents the probability state of system when not performing error checking per access or service time and the second term represent probability state of system when performing error checking per access time. The term $\bar{q}$ is the probability of performing error checking per access, $0 \quad q \quad 1$, is the rate an access operation is serviced by the system, and is error/recovery procedure execution rate.

$$c(t) = \sum_{j=1} \left\{ \Pr_{(j,0)}(t) \quad \bar{q} \quad + \Pr_{(j,0*)}(t) \qquad \right\} \tag{1}$$

Using the proposed Markov model in this paper, one can analyze the frequency on error checking/recovery effect on systems with the goal to maximize number of operations without fail on controlled mission time. The model can also be used to have maximum reliability with the minimum performance requirement. These objectives are within the assumption of same mean rate and distribution (exponential) between service time per operation and time required to do the error checking/recovery procedure; and the occurrence of consecutive error is approximately half of the average mission time period.

The conclusion from the paper are (1) as the error checking rate is higher than the service rate, performing error checking per access ($q = 1$) is recommended since overhead of error checking is relatively low but this applies vice-versa when error checking rate is lower than service rate then it is recommended to check periodically ($0 < q < 1$); (2) when mission period is longer, the periodical error checking rate has to be shorter in intervals (higher q rate) because it requires more checking to prevent a system failure; (3) and selecting optimal q rate with dynamic parameters will require dynamic q rate to obtain best value.

2.5 Prognostics and diagnostics of CE over different dependability networks

The analysis for assigning agents based on different dependability network is needed since there are multiple types and ways to set up CE detection network. A study regarding CE prognostics and detection with respect to CE prevention and diagnostics, respectively (Chen and Nof 2007), conducted a model based on 16 CE states and applied to CEPD logic over four different networks. It is expected that agent-based modeling approach is better than object oriented approach and decentralized CEPD

Conflict occurs when the constraints violates in two or more units in a system. Mostly the method to detect conflict was using layered constraints such as: goal layer, plan layer, belief layer, task layer, and sub-task layer (Ceroni and Velàsquez 2003). The CE detection and resolution in this case classifies the conflict based on detection and solution mechanism. This helps to detect CE in design phase as the complexity rises in product and service. However, a general CEPD method has not been widely researched yet.

There are three approaches to manage faults for process monitoring, they are: analytical approach, data-driven approach, and knowledge-based approach. Analytical approach uses detailed mathematical models by comparing the observed features that correlates with normal operating conditions or modified conditions. Data-driven approach uses large amount of data and apply statistical tools in univariate or multivariate techniques. Knowledge-based approach uses qualitative models such as: causal analysis techniques; expert systems; and pattern recognition techniques to detect and analyze faults (Chiang, Bratz, and Russell 2001). Knowledge-based is applicable when detailed mathematical models not available in the system. All of these three approaches, however, do not explicitly give understanding comparison between conflict and error. They require specific methods in order to detect CEs, and it takes time and complexity to find appropriate method for a system that has to be analyzed first based on its size, complexity, and flow work. Some research has been conducted on fault detection and diagnostics algorithms, which comes into centralized and decentralized algorithms. Centralized algorithms has major weakness as most information and algorithm process controlled centrally, which proven to be inefficient and difficult. Decentralized, however, has been proven to be more effective than other algorithms.

In order to detect CEs, it is important to map and understand the network topologies and its dependencies (Chen and Nof, 2012b). The network is task-driven and tasks have to be completed through collaborating units. Task dependencies are the collaboration ways between collaborating units and there are six collaboration types: Cooperate to provide, cooperate to receive, one-to-one dependency, one-to-many dependency, many-to-one dependency, and many-to-many dependency. To illustrate this into different kind of network, four networks, Fig. 3, with ten collaborating units are constructed for this case study.

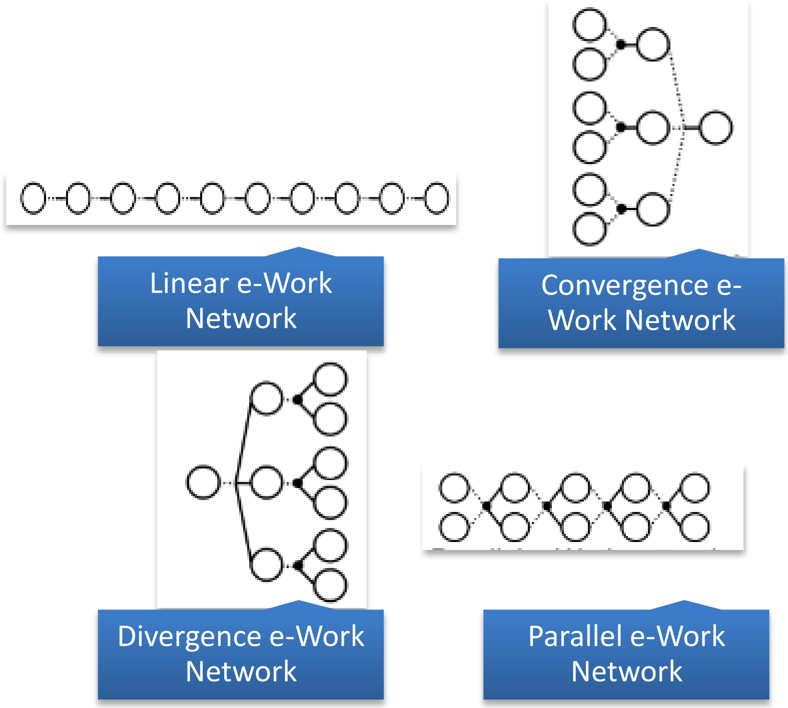

Figure 2.3 Various e-Work Networks with Different Configurations of Dependencies

The result of the CEPD simulation logic based on the four networks in the case study shows that divergence network has lowest CEPD time. It has consistent result in low until high dependability between collaborating units, shows the logic is robust for complex networks. Convergence is second best, followed by linear network until it reaches higher dependability then parallel network (better in high dependability than linear).

2.6 Framework on tool sharing administration

Inspired by collaborative control theory (CCT), this study focuses on collaborative assembly that is able to improve balance-ability and flexibility throughout assembly lines by using tools sharing between bottleneck and idle workstations. In this case, a tool can be human operator, robot or machine to process the tasks, depending the level of automation in the assembly line. The study for collaboration between human and machine-based agents is important (Klein, 1997). Balanced assembly line means that the overall workload in workstations is equally distributed but in practice it is difficult or almost impossible to fully balancing assembly lines. Flexible assembly line means increasing throughput without utilizing additional resources, despite disruptions in the system.

The model is inspired by collaborative tool sharing work and best matching decision protocol off-line so the current model is upgraded into real-time tool sharing and best matching with the enhancement from collaborative assembly framework automation. By using bi-objective mixed-integer programming (BOMIP) model, the off-line planning on tool sharing and best matching decision extended to provide information and control updated continuously.

The two objectives for the model are to give solution that enhance the assembly line balance-ability and increase system flexibility on dynamic changes and complexities. The decision-making autonomy comes from integration of centralized planning and decentralized control, thus increase the system performance. The framework developed as: generating off-line plan using BOMIP model, control mechanism triggered during time interval to monitor and update the plan, and provide feedback for future plan. In order for the model to be effective in communication and interaction, collaborative protocol so it controls the tools sharing activities and optimize the decisions in real-time.

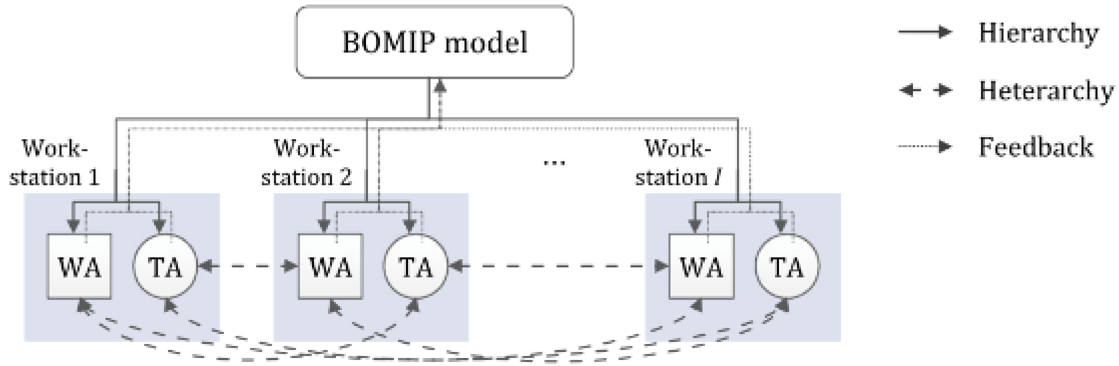

Figure 2.4 Collaborative Multi-Agent System Architecture (Moghaddam and Nof, 2014)

The model is tested in three different scenarios: no collaboration, static collaborative assembly, and dynamic collaborative assembly. Paired *t*-test analysis is applied for validity check and the significance shows that dynamic collaborative assembly outperforms the other scenarios significantly in terms of mean cycle time.

2.7 Summary

Studies regarding CE management and agent deployment in previous works have not considered a case study simulation for quality control inspection trade-off between performance and reliability. The collaborative control in these works did not compare batching and one-by-one inspection performance and reliability.

Enhancing reliability towards performance on previous work focuses on error checking on storage system algorithm. The reliability enhancement has not reached into an inspection network system in production/service industry.

Resource tool sharing provides an effective tool for dynamic assembly lines. It is a good model for the design of quality control in network topology comparison. The model involves different kind of inspection topology and CEDP simulation based on real data. The BOMIP model also highlights the performance versus reliability trade-off.

CHAPTER 3. METHODOLOGY

3.1 Introduction

The data collected were analyzed based on the CE pattern, distribution for the flow, and resources available in the department. All of the data collected manually in a furniture company but the general framework is suitable for manufacturers with high amount of prototyping and item types. Beneath the item types, there are components that have gone through different processes inside the facility. Project scope for this research has been reduced into a single, critical department to conduct the data collection, analyze the processes, and evaluate the results. From discussions with plant managers and quality control department, important CEs detected in the finishing process are mostly faulty parts from laminating department. The delays that are present in the facility are the aftermath from faulty components that needs to be inspected and repaired, which is an issue for scheduling in terms of queue and resource allocation. It is important for the managers to solve the cascading failures that result in assembly line and finishing line inconsistency utilization; uncontrollable off-line repairs; and buffer inspection “rush” performance.

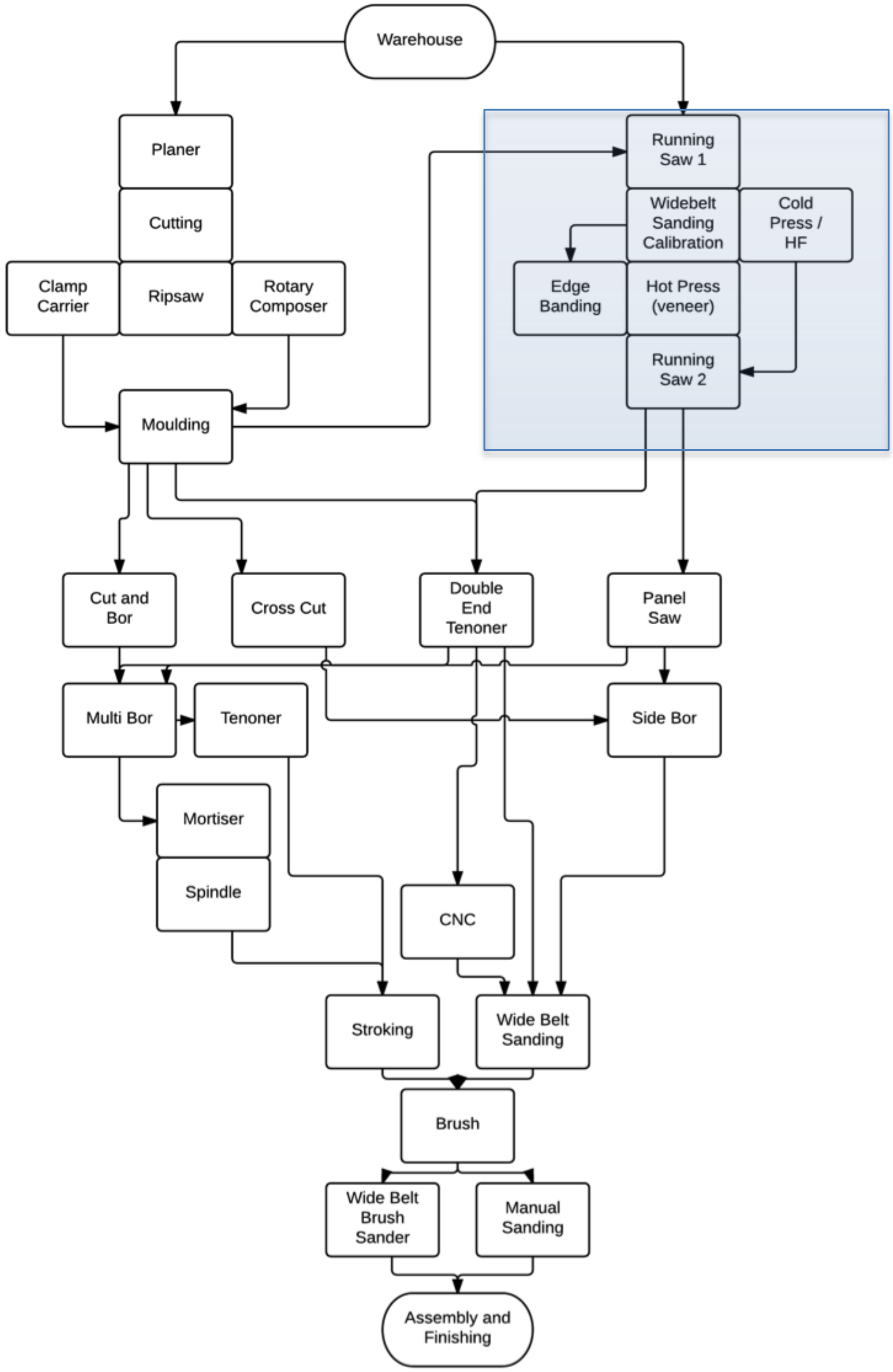

Figure 3.1 General Process Flow in Facility with Box Highlighted Showing the critical Laminating Department to be simulated

The flow chart figure shows the general flow work in the facility from the post-design phase until packing phase. The flow work for white wood (pre-finished) production shows the general complexity on scheduling and management when the facility handles 30 product types (items) and each product type has 10-50 components weekly. Each part undergoes different process sequence and cycle time. There are two types of furniture raw material processing, where one is solid wood production and the other is lamination production (or so called panel line). There are many errors in both departments but most of the errors lies in the raw material defect. However, the cascading defect present in the facility happens in the finishing line and most CEs that are detected and recognized are from the lamination department. In Section 3.2, the CE analysis table shows the types of CE and the recovery process when detected. There are two types of CE recovery in this case, which are: repair and replace.

Fig. 3.1 with the highlight box indicates the experiment focus: Where to conduct, analyze, evaluate, and remodel for the general flow work in the facility. Fig. 3.2 shows the complete process of laminating department.

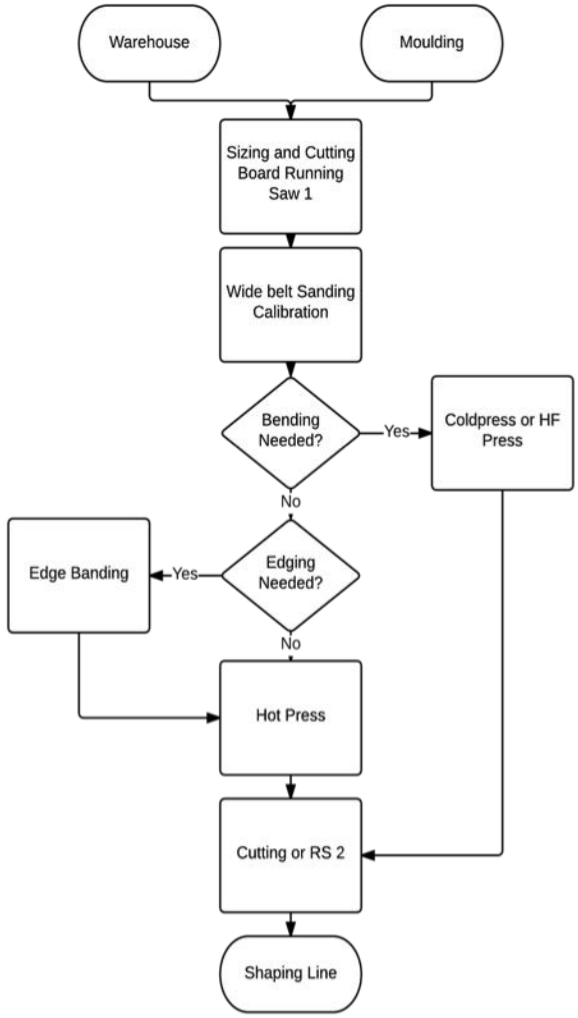

Figure 3.2 Laminating Process Department Logic Flow Chart

The assumptions for this department are as follows:

1. The errors occurring in the process are random and based on the component success/fail ratio
2. Material handling does not impact the error probability
3. QC agents are assigned to station *j* for inspecting the parts after process *i*

4. The transportation for parts between processes is using fitted distribution based on time study
5. The entire process that goes out of the department is considered post manufacturing finished goods (FG).

The complete list of processes for laminating department in this particular facility consist of warehouse (WH), running saw for board (RS1), wide belt calibrator (WBK), hot press with glue rolling (HP), cold presser (CP), running saw for laminated board (RS2), and edge banding machine (EBAND). The part leaves the department based on the product design drawing process's sequence and moves into the last station or buffer station and is ready to move to the next department.

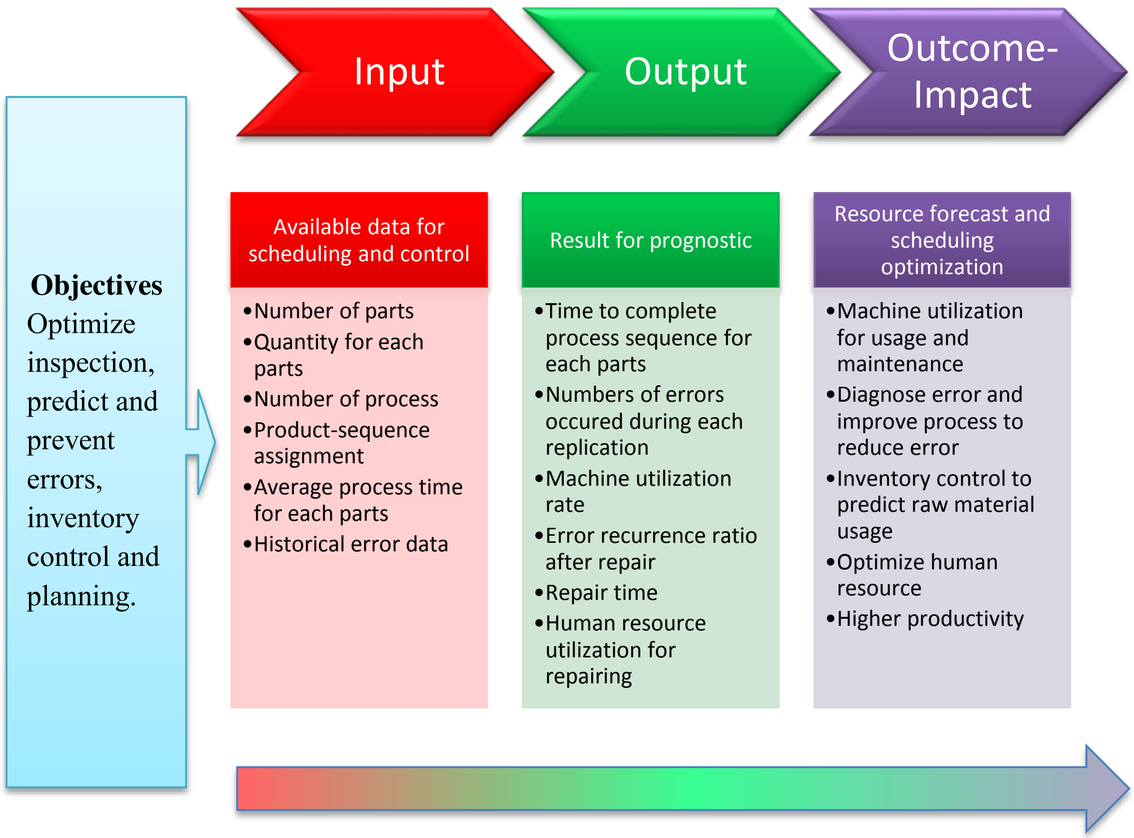

Figure 3.3 Model Logic Flow

3.2 CE analysis

The error is specifically in each process, while the conflict occurs when the error is detected in another collaborating process. The recoveries only have two categories in general, for simplicity: repair or replacement. The time study for parts routing, detection, and recovery process time has been conducted and all of them are fitted into distribution from a simulation model software called Input Analyzer; later in Section 4 it will be discussed further. The error and recovery analysis in Table 3.1 shows the error conditions and recovery method that exist in the department.

Table 3.1 Error and Recovery Analysis

Process	**Description**	**Error**	**Recovery**
WH	Warehouse of fiberboard, glue, and veneer	Veneer crack, crown defect, and decompose	Repair by stitching or replace
RS1	Running saw 1, cuts boards for the desired measurement	Undersize or oversize due to unstable board moisture content	Replace undersize, cut oversize to desired measurement
WBK	Wide belt calibration, calibrating belts and veneer to have smooth surface for glue application	Over-sanding or under-sanding	Replace over-sanding and change settings on under-sanding
HP	Hot pressing machine, common for apply veneer layer on surface board top and bottom.	Delamination (DL) and veneer gap (Budakci, 2010).	Delamination and veneer gap repairing manual attachment, replace on severe gap and DL.
RS2	Running saw 2, cuts finished boards	Not available	Not available
CP	Cold pressing machine, use for bending or thick veneer laminating	DL, veneer gap, and internal crack.	Replace veneer on severe DL and gap, otherwise repair
EBAND	Edge banding; apply veneer on the side of the board	DL and chipping	Replace veneer on severe DL and chipping. Minor error goes manual repair

Conflict happens when the error detection missed and cascades the problem in other process or collaborating unit. The detection time and cost increases because diagnosing more than one process error source increases the difficulty and the lost value also increases as the component went through more value-adding process. Repair and recovery process cost increases as well because the complexity increases as more process and materials are added into the conflicted component. Based on this rational, the mean time for cascading CE assumes on using exponential increase behavior, while the number of cascading CE event decreases when parts are going through more inspection stations.

3.3 Strategies for inspection assignment

The proposed strategies for comparison are centralized station, decentralized stations, and combination of centralized and decentralized stations that are based on preventability measure for better coverage and less demand on available resource. Each of the strategies is given piece-by-piece inspection and batching option for comparison on time to completion and resource allocation efficiency. The current strategy that exists in the facility uses batching strategy in order to decrease negligence factor and resource fatigue on QC agents. Each strategy has different limited number of QC agents as the resource, later discussed in Section 4. One-by-one strategy is considered into the design for future framework on stationary autonomous agents if cost-benefit evaluation permits.

Another parameter for comparing the performance between strategies is the time to completion *TTC* towards the targeted quantity. FMF as a supplier for a customer has to maintain its reliability both in time and quality. The objective function is to minimize the time to completion and total cost, as the main two measures for DM, and the number of inspection station. The efficient assignment model objective is to minimize the decentralized stations to achieve significant lower time with similar preventability and reliability level.

The inspection assignment for the simulated department is shown in Fig. 3.4. The efficient assignment allocation is based on the CE historical data. For each process, the error percentage is analyzed and the inspection station will be assigned if the percentage exceeds the desired level, which is defined in the simulation model. The difference between decentralized and efficient inspection assignment is the inspection station reduction, which benefits in terms of performance.

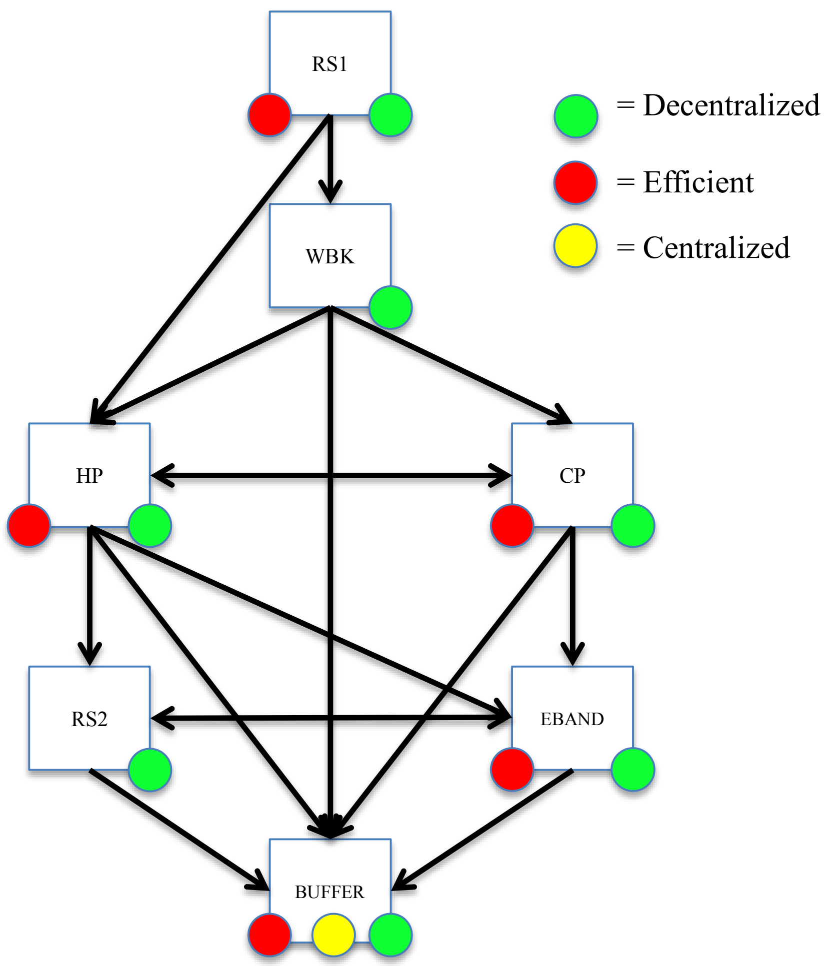

Figure 3.4 Inspection station assigning based on three scenarios

To calculate the cost for comparing the best scenarios between the strategies, the total cost TC function is categorized into three parts: repair cost, replacement cost, and post-manufacturing penalty cost, and denoted as:

$$TC = TF + TR + TP \tag{2}$$

where TF, TR, and TP denote the total repair cost, total replace cost, and total post-manufacturing penalty cost, respectively. The breakdown for each costs denoted as:

$$TF = \sum_{i\in I} \sum_{j\in J} u_{ij} SC_j F_i \tag{3}$$

$$TR = \sum_{i\in I} \sum_{j\in J} v_{ij} SC_j R_i \tag{4}$$

$$TP = wPO \tag{5}$$

Where u_i, v_i, and w denote the weighted cost for repair after process, weighted cost for replacement after process, and weighted post-manufacturing penalty cost, respectively. The cost for each repair F_i and replacement R_i is sum of the product of weight of the cost with inspection station binary variable function and the quantity of parts needs to be fixed/repair F_i or replace R_i. Repair has lower weighted cost than replacement cost and post-manufacturing penalty has much higher concern than other type of cost due to the value, time, and trust invested in it. The binary variable function denoted as:

$$SC_j = \begin{cases} 1, \text{if inspection station } j \text{ assigned after process } i \\ 0, \text{otherwise} \end{cases}, \forall i \in I, j \in \tag{6}$$

s.t.

$$\sum_{j\in J} SC_j \leq J, \tag{7}$$

where the total number of SC_j has to be equal or lower than the set of inspection station J. When SC_j has the same value with J, the scenario is a full-decentralized inspection station assignment. The set of process I has smaller number than J in this study because there is final check in the buffer zone.

3.4 Performance Metrics

Preventability $V_{scenario}$ is a measure for the number of defect that can be prevented before the last station or buffer station. Preventability is specifically measured for each strategy and denoted as:

$$V_{\text{Centralized}} = 0 \quad (8)$$

$$V_{\text{Decentralized}} = 1 - \frac{D_{\text{Decentralized}}}{D_{\text{Centralized}}} \quad (9)$$

$$V_{\text{Efficient}} = 1 - \frac{D_{Efficient}}{D_{Centralized}}, \quad (10)$$

Where $V_{Centralized}$ Centralized does not have preventability since there is no inspection station before the last station. The denominator for the function is Centralized assuming simple comparison for preventability between strategies. By comparing the $V_{Decentralized}$ Decentralized and $V_{Efficient}$ Efficient assignment with the Centralized, the preventability is determined.

Reliability RE gives a measure for DM measuring the capability for the department on delivering promising quality product for evaluation purposes. Reliability is denoted as:

$$RE = 1 - \frac{PO}{FG}, \quad (11)$$

Where PO is the total number of defect by the department, assumed as post manufacturing; FG is the total number of finished goods manufactured.

The simulation model results were put into Minitab for comparing the four results to check the mean difference significance. The confidence interval level is set to 95% using pairwise t-test. The inspection stations were modeled into the simulation software assuming that the efficient strategy eliminates inspection station where the CE rate and recovery cost is low.

CHAPTER 4. SIMULATION MODEL

4.1 Introduction

With the probability and distribution for the CE and each process in the department, a model based on the FMF was simulated using ARENA simulation tool to acquire four performance metrics comparison on CE QC agent assignment with three strategies mentioned before. The model has data driven input that is based on one month production schedule and the time study result is used for the mean in each process. With unavailability data on standard deviation for each parts service time in the process, it is assumed that the service time follows an exponential distribution for simplified analysis (Balakrishnan 1996). The model input for the CE probability distribution is based on the data collected. The results can provide planning and control tool for production planning and inventory control (PPIC) department for assigning inspection station.

With the data collected for components' quantity, the process went through each respective machines, service time, transportation time, and number of CE non-cascaded and cascaded in the department; the model use the mean value from the data for the times and applied it into a random distribution; and use the cost function on the error recoveries. These simple assumptions approach would be able to approximate the best strategy.

The model also assumes the frequency for having CE is lower when components passes more inspection station using normal distribution with low standard deviation to avoid the chance of surpassing the 100% limit in the Decide module. Overall, the simulation model can be introduced as a three-stage model. The first stage is to create triggering components (entities and counter) to initialize the simulation; the second stage is to sort and assign the parts with the preset information; and the third stage is to make the parts flow into the assigned process sequence, and model data record after all processes are completed.

There are six different types of simulation models and they comprise three different strategy categories: Centralized, Decentralized, and Efficient inspection assignment. Each strategy has one-by-one and batching checking, the batching requires 25 parts in the inspection queue. The size 25 was determined as the particular number is the mode and close to the average pallet size in the FMF's laminating department.

The Centralized strategy has inspection station similar to the convergence network structure, where all inspection occurs on before buffer or after completing all process. Centralized inspection has higher CE probability among other strategy as it has lowest preventability and CE coverage.

Decentralized strategy has inspection station after each process as the inspection concentration spread through the entire department. The resource utilization is heavily dependent on the number available resources; therefore higher resources results better in time to completion. It has the lowest QC failure chance as the detection and recovery are equally distributed.

Efficient strategy for the particular case based on the data has inspection station after HP, CP, and EBAND process. The station assignment is based on higher than standard limit error chance conducted from data, logic from Fig. 4.2. The inspection assignment structure has characteristics from both divergence and convergence network, it diverges after first process, converges for last inspection.

4.2 Model Illustration

Each simulation model has total of 128 types of components with total quantity of 8175 and the error rate is based on the error report collected. To represent these components, entity-assigning model was used. These 128 Assign modules to assign each component of one month's production product to the planned processes and the value for service time in each process, parts quantity, and entity sequence that corresponds with the preset sequence available that were created based on the laminating job. The service time for each part type is different due to its different dimensions and wood material. The service time uses the data from time studies that were conducted during prototyping. There are combinations of sequences in the department that might not be applicable in this specific simulation model, however, the data collected in the specific time frame reflect the majority common working sequence typically present in the facility.

Table 4.1 Step-by-step Description on the Simulation Model

Step	**Description**
1	Create number entities with same value of parts
2	Create counter for condition in separating entities
3	Separate and sort entities to Assign modules. Later the Assign modules will store value for each entity. The ascending order follows with data working order.

Table 4.1 Cont.

4	Assign the entities into each part and store value for quantity, process time in different process, and process sequencing.
5	The duplication follows the quantity variable that preset in the Assign module
6	The process that each part has to go and it follows the sequence order that has been set in the Assign module. The average working time for each process has been preset in the Assign module. The sequence ends to last station to finish the whole process. The record is to counter and terminate the simulation after all quantity is finished working.
7	The inspection sub-model put after each process to detect and repair or replace part if CE present. Fig. 4.2 below shows the CE model for certain parts and the repair process that it has to go through after detected. The detection has the probability of error based on the data. For efficient model, decision model separates the job contains sequences that requires inspection (error checking assigned based on station inspection model)

Product assignments to fulfill the queue finished on a target quantity and terminates as the department finishes 5000 parts. This particular number is chosen as termination point since the first process queue is depleted once the department processed 5000 parts; so the utilization of resources and inspection processing data is observed during the middle of the projected month production.

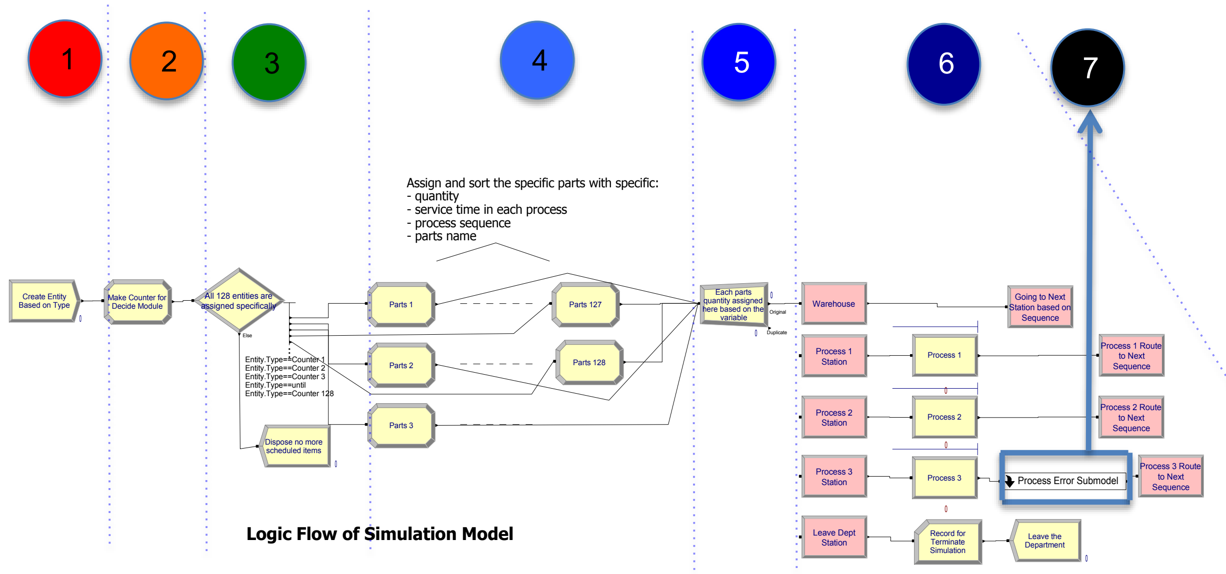

Figure 4.1 ARENA Model, Illustration from Table 4.1

The errors in each process are assumed to occur following a normal distribution with low standard deviation to avoid negative values on Decide module. The data-based probabilities are put into the random normal distribution to ensure the errors and recovery events are not deterministic. Each strategy has a different error mean in the probability, based on the assumption for having CE in different stations, and cumulative inspection that reduces chance of failures. The different error means are justified based on the number of available inspection station where the less stations are assigned, the higher probability for CE to occur. With higher number of inspection station, the Decide module will have higher pass rate than lower inspection station. Centralized method has normal distribution with average of 92.15% pass rate through post-manufacturing, same rate as the current laminating department. In contrast, Decentralized method has 98% pass rate through post-manufacturing as the preventability is spread throughout other processes. The post-manufacturing defect for Centralized is 0.1% higher than Efficient and 0.2% higher than Decentralized with low standard deviation.

The Batching module is created before the inspection occurs to wait for 25 parts to be batched into one batch, and then perform the inspection with five times the one-by-one inspection time. The batching is temporary as later after inspection the Separate module will retain original entity values. Batching is expected to have less preventability than one-by-one because batching has greater standard deviation than one-by-one, assuming sensors do not have significant variability.

The inspection allocation is decided based on CE relation in Fig. 4.2. By having a reliable process (low CE rate), the inspection station is eliminated. In this case study, the cascading CE effects are mostly from HP, CP, and EBAND. Other process stations have low CE rate and high volume, which is also another consideration factor to reduce the inspection station. By doing it, the QC agents have more relaxed utilization than having fully Decentralized inspection.

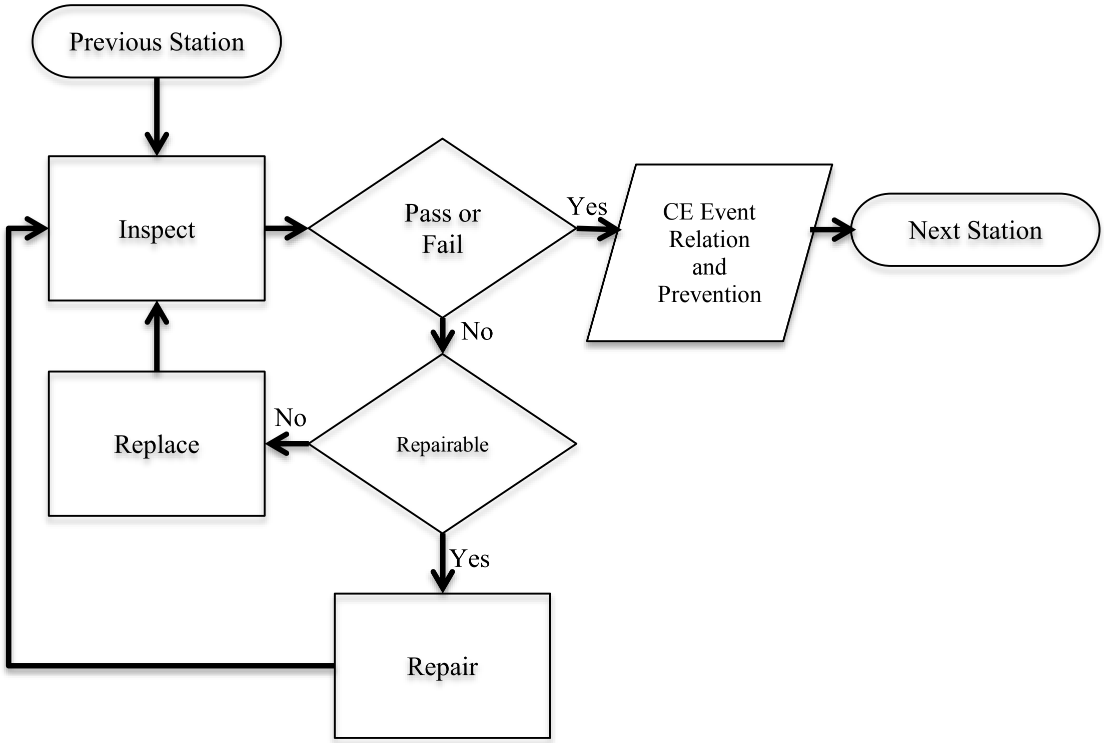

Figure 4.2 Inspection Assigning Model

The resource for inspection is identified as “QC person” and with the assumption on having to move back and forth, the transportation time is assumed into downtime after QC inspected each piece or batch. The available QC as a resource is 2, 3, and 4 for the simulation for comparison purposes. Currently in the facility there are 3 QC agents available in the department however by having less and more QC available in the simulation potentially helps DM on evaluate the QC allocation performance on different project batches. It is assumed, for future references, the one-by-one inspection method uses a robotic sensors to detect errors and can provide result on its worth for investing such technologies.

CHAPTER 5. RESULTS EVALUATION

5.1 Introduction

This chapter discusses the simulation results and measures from methodology for comparison between the alternative strategies. The discussion begins with explaining the observed results and the significance for the effective assignment compared to the Centralized and Decentralized strategy. The results are presented in charts and the validity tests are presented in tables.

5.2 Simulation Results Evaluation

The experiment shows that having parts inspection one by one in performance on time to completion is better, however, there are inconsistencies for performance on post-manufacturing defect. Decentralized and Efficient strategy on batching show lower post-manufacturing defect than one by one checking. Since post-manufacturing cost is relatively very significant towards the total cost function, Centralized strategy is not preferred.

In inspection method category, one-by-one has the lower time to completion compared with batching inspection. As in inspection station assignment strategy, efficient logic has average low time for batching in any case for the available QC agent as resource but have inconsistency result for one-by-one inspection type. The result is different with what is predicted because the assumption is batching saves QC time in transfer from one station to another. The experiment shows the batch size fulfillment makes QC agents have to wait then inspect and causing other batch waits for the QC agent when an agent is not available.

The results show that Decentralized prevent more post manufacturing error than the other two scenarios, but the completion time taken is significantly slower than other scenarios. The result clarifies the assumption that reducing inspection station can benefit in performance. However, there is only slight difference in percentage for reliability of the system after reducing the inspection station. This is predicted since having more resource for Decentralized is better for covering all the workstations. Having lower resources is preferred since it costs less in terms of salary and more stable in terms of qualitative and standardization bias. Later the pairwise *t*-test showed statistical significance on the difference between the means for reliability.

The comparison of the inspection methods by batching assuming using human inspector as QC agent and one-by-one inspection assuming using robot inspector, highlights the strength in one-by-one inspection on lower finish time and higher preventability in general. Batching inspection requires waiting on the tool or resource having each batch to pass QC standard. With less QC agents, the time taking to wait for QC inspection pass is longer. The tables (5.4 & 5.5) show that batching has longer time to complete. This is due to QC agent waiting for batch size to be fulfilled and the waiting cascades to other processes.

Pairwise *t*-test is applied to compare the mean values of each scenario for four performance measures: time to completion, preventability, reliability, and cost. The test used Minitab as a statistical software tool to check the mean difference and its significance between the results.

Table 5.1 Pairwise *t*-test on Preventability between Decentralized and Effective Strategy

Inspection Method	QC	Efficient Mean (SD)	Decentralized Mean (SD)	Mean Difference P-value
Batch	2	0.643 (0.028)*	0.6059 (0.032)	< 0.05
	3	0.6379 (0.031)*	0.6097 (0.0337)	< 0.05
	4	0.6437 (0.0298)*	0.6055 (0.0279)	< 0.05
One-by-one	2	0.6512 (0.02963)*	0.6187 (0.0349)	< 0.05
	3	0.6479 (0.0309)*	0.6245 (0.0314)	< 0.05
	4	0.6538 (0.03)*	0.6207 (0.03)	< 0.05

* = significant with 95% confidence interval.

Table 5.2 Pairwise *t*-test for Reliability between Decentralized and Efficient Strategy

Inspection Method	QC	Efficient Mean (SD)	Decentralized Mean (SD)	Mean Difference P-value
Batch	2	0.9977 (0.0006)	0.9979 (0.0007)*	< 0.05
	3	0.9976 (0.0007)	0.9981 (0.0005)*	< 0.05
	4	0.9976 (0.0007)	0.998 (0.0006)*	< 0.05
One-by-one	2	0.9977 (0.0007)	0.9979 (0.0007)*	< 0.05
	3	0.9976 (0.0007)	0.9981 (0.0005)*	< 0.05
	4	0.9975 (0.0007)	0.9979 (0.0006)*	< 0.05

* = significant with 95% confidence interval.

Table 5.3 Pairwise *t*-test for Reliability between Centralized and Efficient Strategy

Inspection Method	QC	Efficient Mean (SD)	Centralized Mean (SD)	Mean Difference P-value
Batch	2	0.9977 (0.006)*	0.997 (0.0007)	< 0.05
	3	0.9976 (0.007)*	0.997 (0.0007)	< 0.05
	4	0.9976 (0.0007)*	0.9969 (0.0007)	< 0.05

Table 5.3 Cont.

One-by-one	2	0.9977 (0.0007)*	0.9971 (0.0007)	< 0.05
	3	0.9976 (0.0005)*	0.9969 (0.0007)	< 0.05
	4	0.9975 (0.0007)*	0.997 (0.0007)	< 0.05

* = significant with 95% confidence interval.

Table 5.4 Pairwise *t*-test for Finish Time between Decentralized and Efficient Strategy

Inspection Method	QC	Efficient	Decentralized	Mean Difference
		Mean (SD)	Mean (SD)	P-value
Batch	2	79.469 (1.227)*	81.142 (1.0)	< 0.05
	3	79.41 (1.084)*	81.134 (1.046)	< 0.05
	4	79.452 (1.002)*	80.985 (1.018)	< 0.05
One-by-one	2	67.6858 (0.674)*	72.7803 (0.483)	< 0.05
	3	66.9437 (0.7616)	67.1302 (0.817)	0.082
	4	67.0181 (0.881)	67.0542 (0.9493)	0.773

* = significant with 95% confidence interval.

Table 5.5 Pairwise *t*-test for Finish Time between Centralized and Efficient Strategy

Inspection Method	QC	Efficient	Centralized	Mean Difference
		Mean (SD)	Mean (SD)	P-value
Batch	2	79.469 (1.227)	70.807 (1.087)*	< 0.05
	3	79.41 (1.084)	70.703 (1.125)*	< 0.05
	4	79.452 (1.002)	70.791 (1.074)*	< 0.05
One-by-one	2	67.6858 (0.674)	66.9619 (0.788)*	< 0.05
	3	66.9437 (0.7616)	66.9707 (0.8519)	0.798
	4	67.0181 (0.881)	67.0291 (0.8427)	0.923

* = significant with 95% confidence interval.

Table 5.6 Pairwise *t*-test for Cost Function between Decentralized and Efficient Strategy

Inspection Method	QC	Efficient Mean (SD)	Decentralized Mean (SD)	Mean Difference P-value
Batch	2	1764.9 (168.2)*	1706.1 (162.4)	< 0.05
	3	1785 (185.9)*	1657.2 (155.3)	< 0.05
	4	1769.9 (172.2)*	1689.5 (152)	< 0.05
One-by-one	2	1639.5 (153.5)*	1565.3 (152.8)	< 0.05
	3	1662.2 (165.2)*	1539 (152.4)	< 0.05
	4	1659.6 (156.1)*	1575.1 (149.1)	< 0.05

* = significant with 95% confidence interval.

Table 5.7 Pairwise *t*-test for Cost Function between Centralized and Efficient Strategy

Inspection Method	QC	Efficient Mean (SD)	Centralized Mean (SD)	Mean Difference P-value
Batch	2	1764.9 (168.2)*	5543.6 (248.5)	< 0.05
	3	1785 (185.9)*	5467.2 (250.1)	< 0.05
	4	1769.9 (172.2)*	5550.2 (267.9)	< 0.05
One-by-one	2	1639.5 (153.5)*	5042.1 (274.4)	< 0.05
	3	1662.2 (165.2)*	5095.7 (258.7)	< 0.05
	4	1659.6 (156.1)*	5075.3 (257.8)	< 0.05

* = significant with 95% confidence interval.

Centralized detection receives more impact on department's preventability and reliability compared with Efficient and Decentralized method. Decentralized preventability shows much lower than efficient strategy, which is acceptable because the comparison affected by the number of defect. Decentralized as a whole detect more defect than efficient, however post-manufacturing defect is not included so therefore reliability and cost factor has to be considered as well.

The cost function has high values on centralized strategy followed by Decentralized then Efficient. The effect of buffer repair and replacement as well as post-manufacturing penalty cost makes the cost function for centralized higher than every other strategy.

In terms of time, it is expected to have better time for efficient than Decentralized strategy. The pairwise test shows efficient is better option in completion time against Decentralized, especially with lower number of QC agent. It has insignificant difference with centralized strategy.

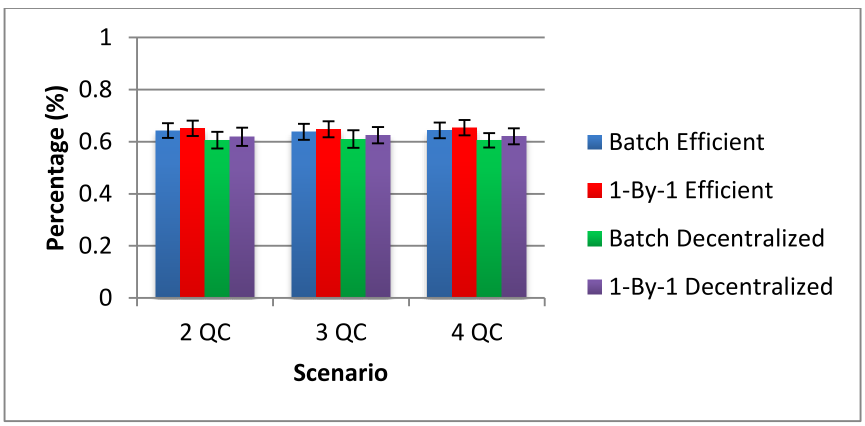

Figure 5.1 Preventability Percentage Compared with Centralized Inspection

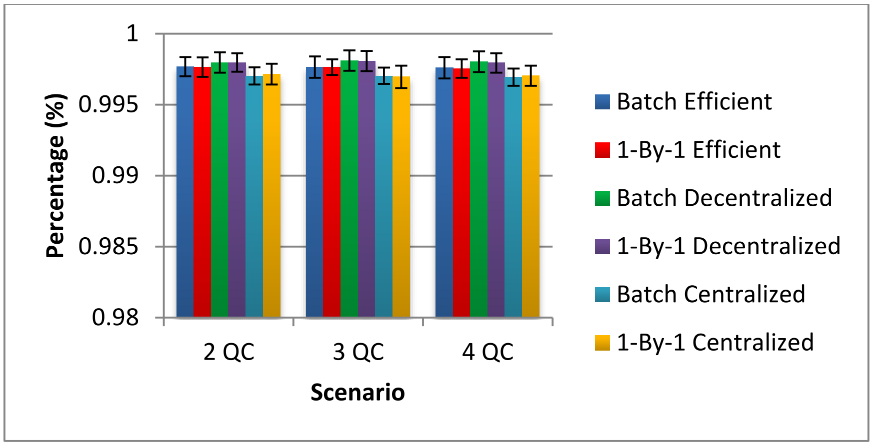

Figure 5.2 Reliability Percentages with Different Number of QC Agent

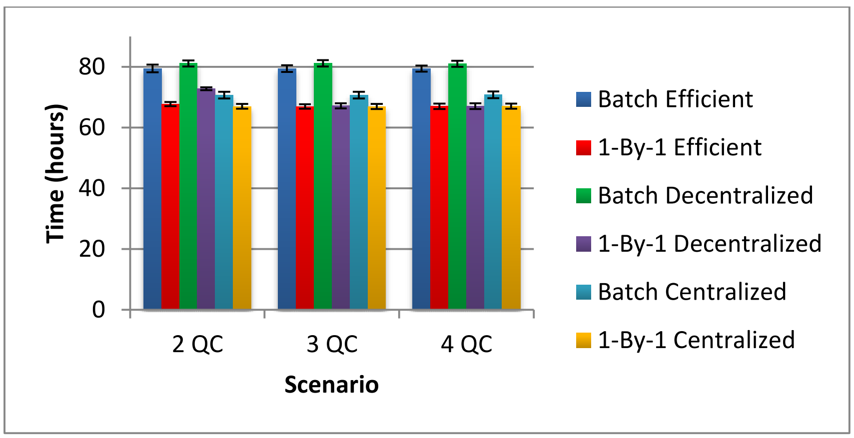

Figure 5.3 Time to Completion Results

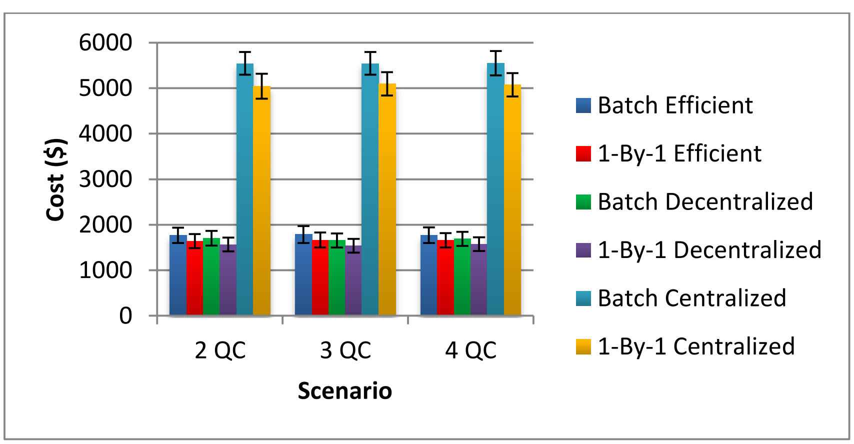

Figure 5.4 Total Cost Results

Another point to highlight is the stability in time completion for one-by-one strategy compared with the batching strategy. The stability measurement in this case uses static stability concept (Becker and Leon, 1988; Lin, Binns, and Lefkovitch, 1986) by using the time completion variance. The variance result (Table 5.8) was analyzed using Minitab. It shows that all of one-by-one strategy's results has lower value than batching strategy.

Table 5.8 Variance Values on Time Completion

Number of QC	Batch Efficient	One-by-one Efficient	Batch Decentralized	One-by-one Decentralized	Batch Centralized	One-by-one Centralized
2	1.0036	0.7758	1.0367	0.9011	1.1529	0.7102
3	1.1748	0.5801	1.0931	0.6674	1.2654	0.7258
4	1.5052	0.4543	0.9991	0.2333	1.6329	0.6222

The preferred strategy based on cost function for batch and one-by-one inspection is the Decentralized strategy. This result is expected, again, because the weighted cost for repair and replace parts is very high in post-manufacturing. Decentralized have the lowest post-manufacturing defect or penalty cost. Therefore, it has significant difference between the other scenarios. Fig. 5.4 shows the cost function results for each strategy and centralized strategy is the least preferred, nearly three times cost difference with other two strategies.

All results show that Batching costs more and takes more cycle time to complete in the simulation. The reliability difference between batching and one-by-one is not significant. Batching shows less preventability than one-by-one due to batching assumed to have more error percentage than one-by-one, assuming sensors do not have variability.

5.3 Analysis of Methodology

This case study on furniture manufacturing implements the Conflict/Error Prevention and Detection (CEPD) model for designing the inspection workflow and task distribution among quality control agents. Compared to the general theoretical CEPD model, the detailed practical implementation has the following specific features as shown in Table 5.9.

Table 5.9 Application of CEPD model in furniture manufacturing case study and comparisons

Comparison category	CEPD framework	Case study in this thesis	Comments/Observations
Definitions	Prevention and detection agents (PDA)	Quality control (QC) agents (humans or robots)	Two types of agents are simulated.
	Conflicts and errors	Defects in products caused by manufacturing conflicts and errors	The manufacturing sequence is a real network of constraints.
	CE propagates according to constraint networks	Defects accumulate through the manufacturing sequences	
	Tasks: Detection, diagnosis, prevention	Tasks: Inspection, repair, replace	In real applications, CEPD needs to be combined with rectification (repair and replace) tasks, to prevent cascading of CE.
Strategy	Ignore CE with negligible cost/damages	Focus the analysis on the department with most critical CE (lamination department in this case)	The strategies are analogous

Table 5.9 cont.

Algorithms	Centralized CEPD	Inspection in buffer	The allocation of agents is a challenge related to CEPD. The theoretical model has not yet addressed this issue. A hybrid approach also needs theoretical development in CEPD.
	Decentralized CEPD	Inspection in every station	
	Not yet available	Efficient (hybrid) inspection	
Performance metrics	Preventability of CE	Preventability of defects	The CE propagation can be stopped (prevented) by in-process repairing/replacing failed parts.
	Coverage ability of CE	Reliability of products	The uncovered CEs result in unreliable products that are released to customers.
	Damage caused by CE	Total cost including repair cost, replacement cost, and post-manufacturing penalty cost	Besides the damage caused by the CE, CE's influence also include the time and cost paid to recover the CE.
	Total CEPD time	Time to complete manufacturing	

As shown in Table 5.8, this research is a case study of the CEPD model in practice. Besides validating the CEPD algorithms in real applications, the current work has extended the theoretical model in the following aspects.

1. Rectification is combined with prevention and detection in the management of conflicts and errors;
2. Hybrid centralized/decentralized CEPD algorithm is tested according to the workflow of the manufacturing system;

3. Customer-centric performance metrics (reliability and time to complete) are added into the CEPD model.

CHAPTER 6. CONCLUSIONS

6.1 Conclusions

A cascading undetected CE has been proven to cause drawbacks in manufacturing and service industries. CEDP methods are developed to improve the system in reliability and robustness, and to establish practical considerations and challenges that may lead to further refinement of the DEPD theory. There are two main CEDP types: Decentralized and Centralized, but Decentralized is proven to be more effective than Centralized in general. This study highlights the trade-off between cost, time, reliability, and preventability in six different kinds of scenarios. The proposed scenario has reduced fully Decentralized inspection station in batching and one-by-one in order to get optimal time and cost, as well as maintaining sufficient reliability and preventability.

The efficient inspection station assignment from the study achieves a lower time from batching Centralized and Decentralized strategy. The statistical analyses on the results of the different strategies indicate improvements in inspection time and cost for the efficient station assigning. Decentralized scenario has been proven to be the most reliable, but efficient station assigning reliability is not significantly different, as proven in pairwise test. The time completion for one-by-one inspection method is more stable than batching method and proved by static stability concept.

QC system designer has to analyze the performance trade-off when performing inspection whether it is affecting the reliability and output of the system, especially in an industry where the product are combination of art and engineering. The engineering process quality has to be fulfilled but there are margins for invariability visual look that is needed to avoid monotony products. QC system designer can change the standard batch size in order to save time in transportation coming back and forth from one station to another. Another note for QC designer is to design diagnostic tools and guidance (Christiansen and Knaebe, 2010).

In terms of comparison between the theoretical CEPD and the practical case study (Section 5.3), several observations are made that can help to refine the CEPD theory in the future.

6.2 Future work

1. Optimizing the limit in the binary function for assigning the station, as it can impact on the model in time, preventability, and reliability measures. Future research on the standardized limit for the assignment would improve the CE management model. Deeper the optimization for allocating detection method with a better heuristics or an algorithm that can balance the work of QC agents and performance vs. reliability trade-off in managers desired level.
2. Batching size optimization can be beneficial for QC system designer in order for the agents to save transportation time between one station and another. The optimization has to consider parts dimensions and safety regulations for pallet and material handling procedures.

3. A case study for quality improvability in finishing department (Wang, Arinez, and Biller, 2012) can be useful for focus on batch production and bottleneck based on batch size.
4. Apply the model on autonomous agents for different kind of project segment can be an interesting research since many industries uses the particular agent and the return on investment for such agent will affect the significance in terms of cost, preventability, and reliability. The framework has been developed for one-by-one checks that is ideal for autonomous inspection.
5. In QC agent perspective, the agent variability and service time for inspection has to be studied because the inspection time should be varies by the process type, part dimension, and the difficulty of CE detectability.

LIST OF REFERENCES

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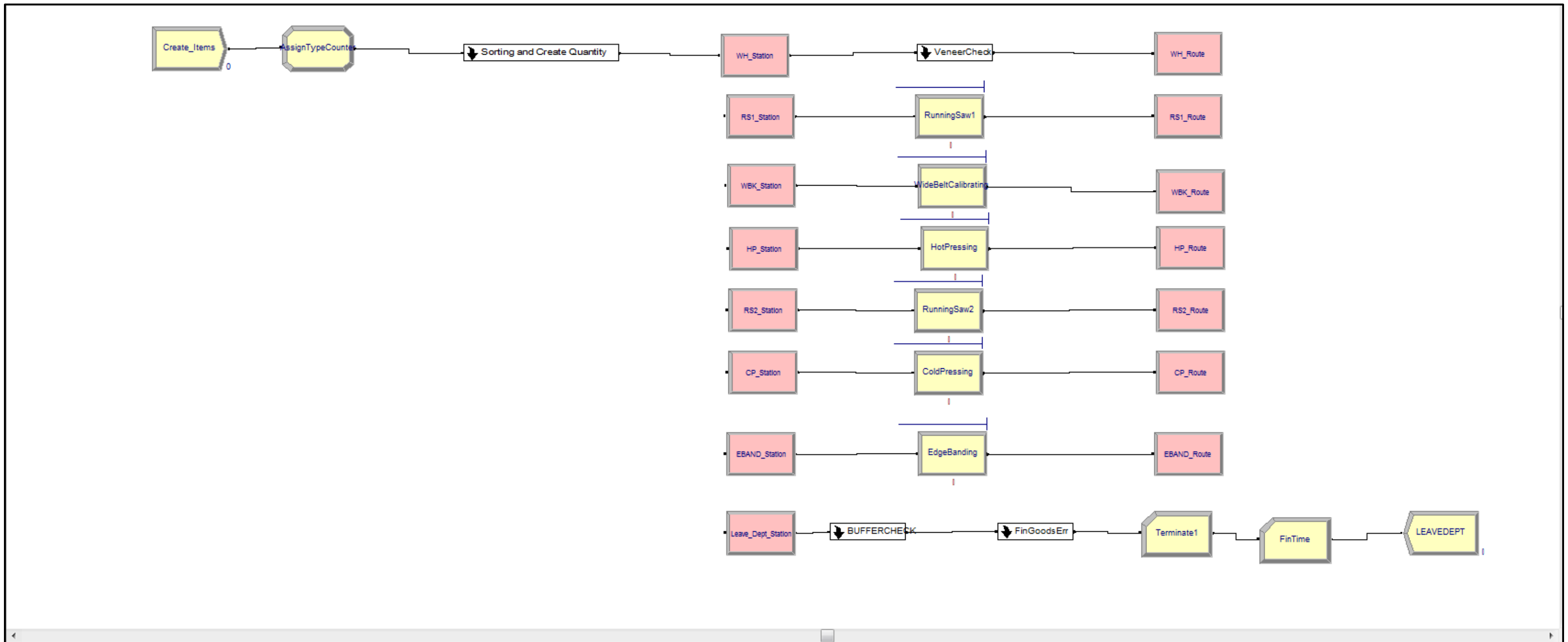
APPENDICES

Appendix A ARENA Simulation Model

A.1 Simulation Model for Centralized Inspection

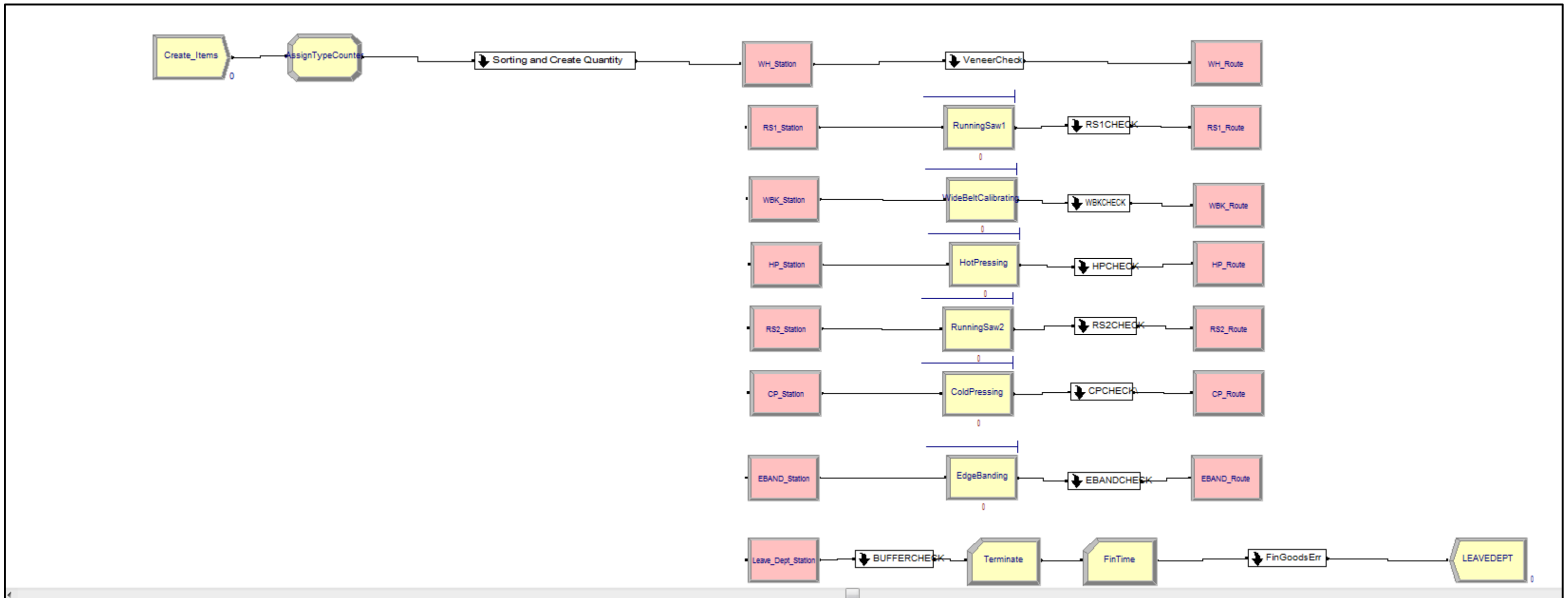


Resource - Basic Process

	Name	Type	Capacity	Busy / Hour	Idle / Hour	Per Use	StateSet Name	Failures	Report Statistics
1	HotPresser	Fixed Capacity	3	0.0	0.0	0.0		0 rows	☑
2	saw1	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
3	WideBeltCalibrator	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
4	RunSaw2	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
5	ColdPresser	Fixed Capacity	5	0.0	0.0	0.0		0 rows	☑
6	EdgeBander	Fixed Capacity	2	0.0	0.0	0.0		0 rows	☑
7	RepairPerson	Fixed Capacity	2	0	0.0	0.0		0 rows	☑
8	QCperson	Fixed Capacity	2	0	0.0	0.0		1 rows	☑

Double-click here to add a new row.

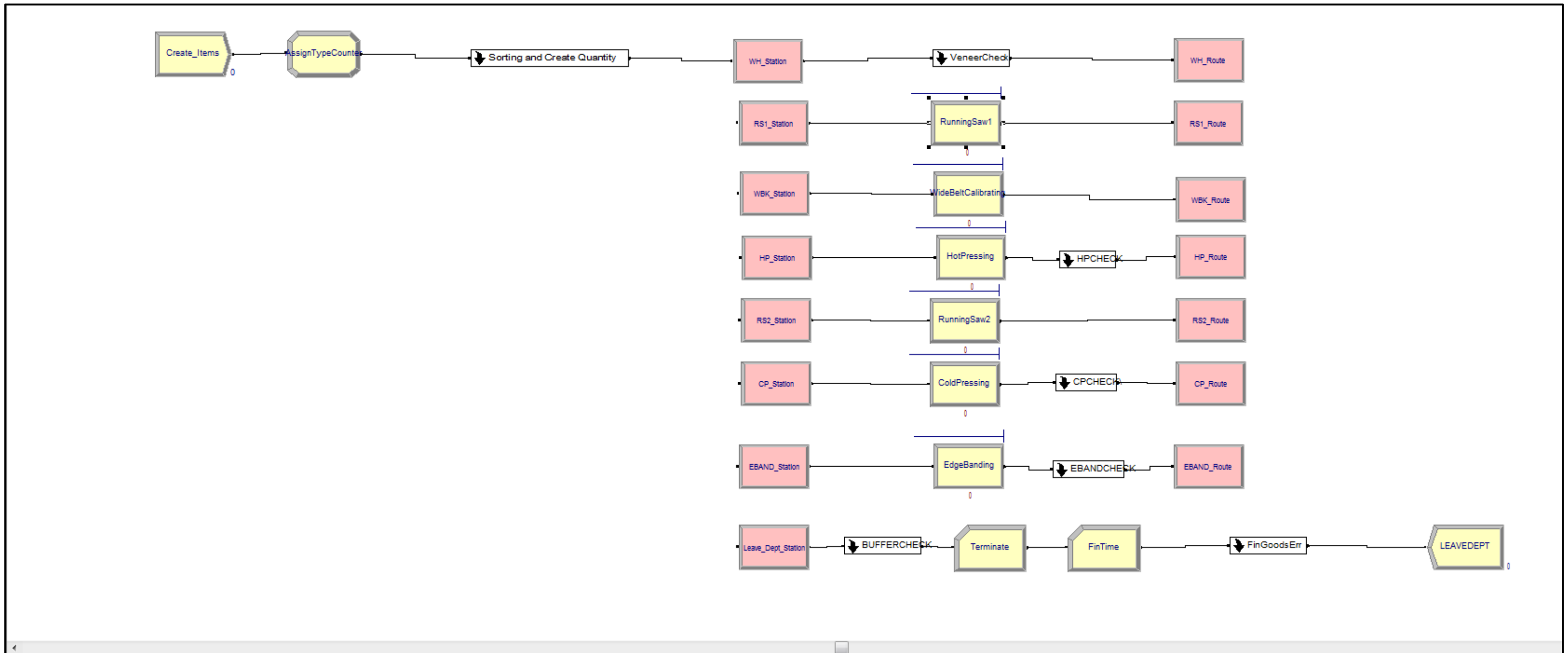
A.2 Simulation Model for Decentralized Inspection



Sequence - Advanced Transfer

	Name	Steps
1	WH_RS1_WBK_HP_RS2	6 rows
2	WH_RS1_WBK_HP_RS2_CP	7 rows
3	WH_RS1_WBK_HP	5 rows
4	WH_RS1	3 rows
5	WH_RS1_WBK_HP_RS2_EBAND	7 rows
6	WH_RS1_HP_RS2	5 rows
7	WH_RS1_WBK_CP_HP_RS2	7 rows
8	WH_RS1_HP_CP	5 rows
9	WH_RS1_CP	4 rows
10	WH_RS1_HP	4 rows
11	WH_RS1_EBAND	4 rows
12	WH_RS1_WBK	4 rows
13	WH_RS1_WBK_HP_CP_RS2	7 rows

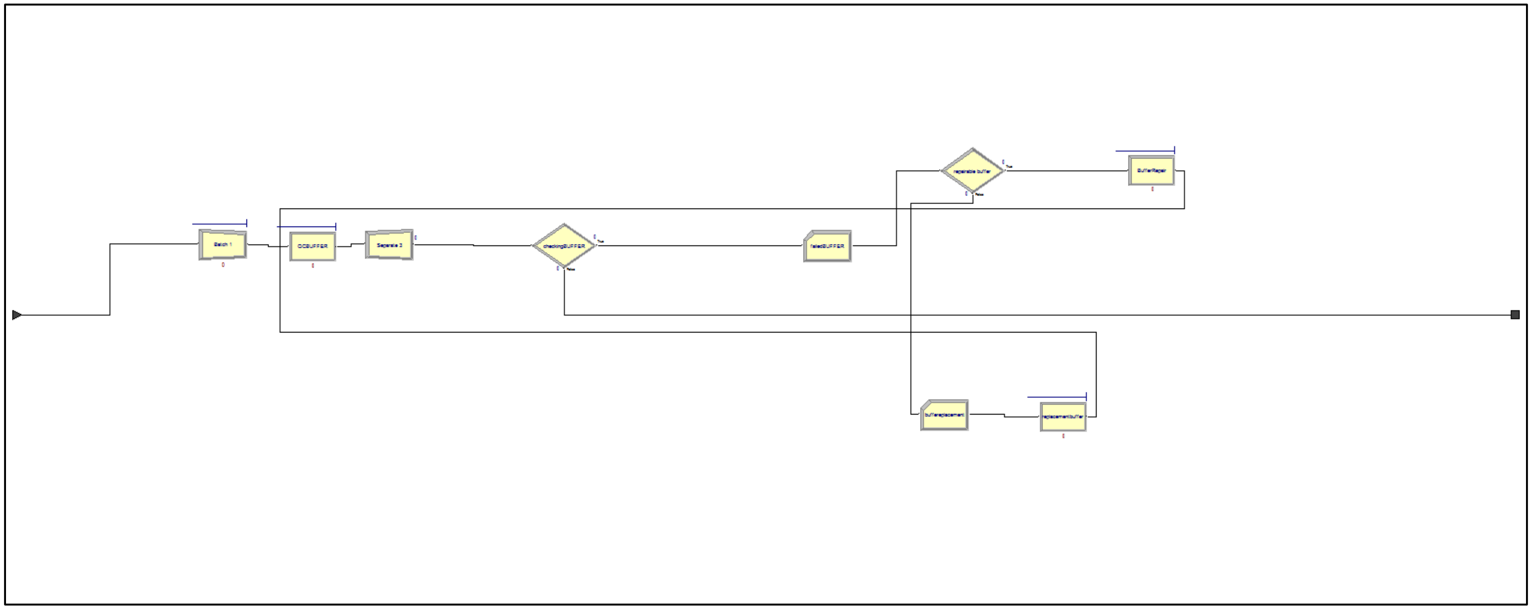
A.3 Simulation Model for Efficient Inspection



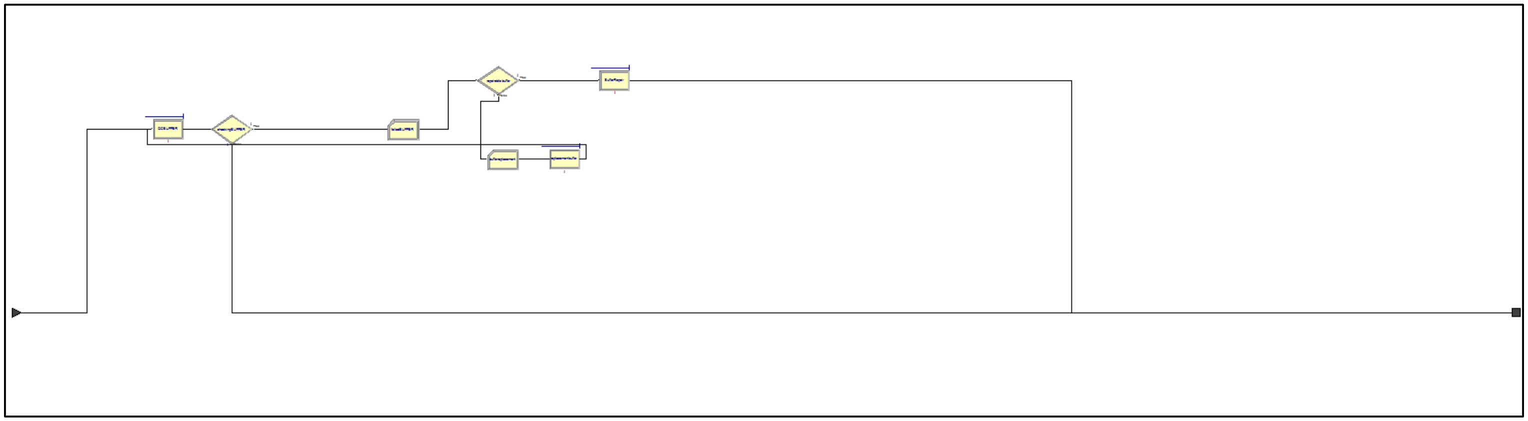
Process - Basic Process

	Name	Type	Action	Priority	Resources	Delay Type	Units	Allocation	Expression	Report Statistics
1	RunningSaw1	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Minutes	Value Added	EXPO(RunSaw1Time)	☑
2	WideBeltCalibrating	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Minutes	Value Added	EXPO(WBKTime)	☑
3	HotPressing	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Minutes	Value Added	EXPO(HPTime)	☑
4	RunningSaw2	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Minutes	Value Added	EXPO(RunSaw2Time)	☑
5	ColdPressing	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Minutes	Value Added	EXPO(CPTime)	☑
6	EdgeBanding	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Minutes	Value Added	EXPO(EBTime)	☑

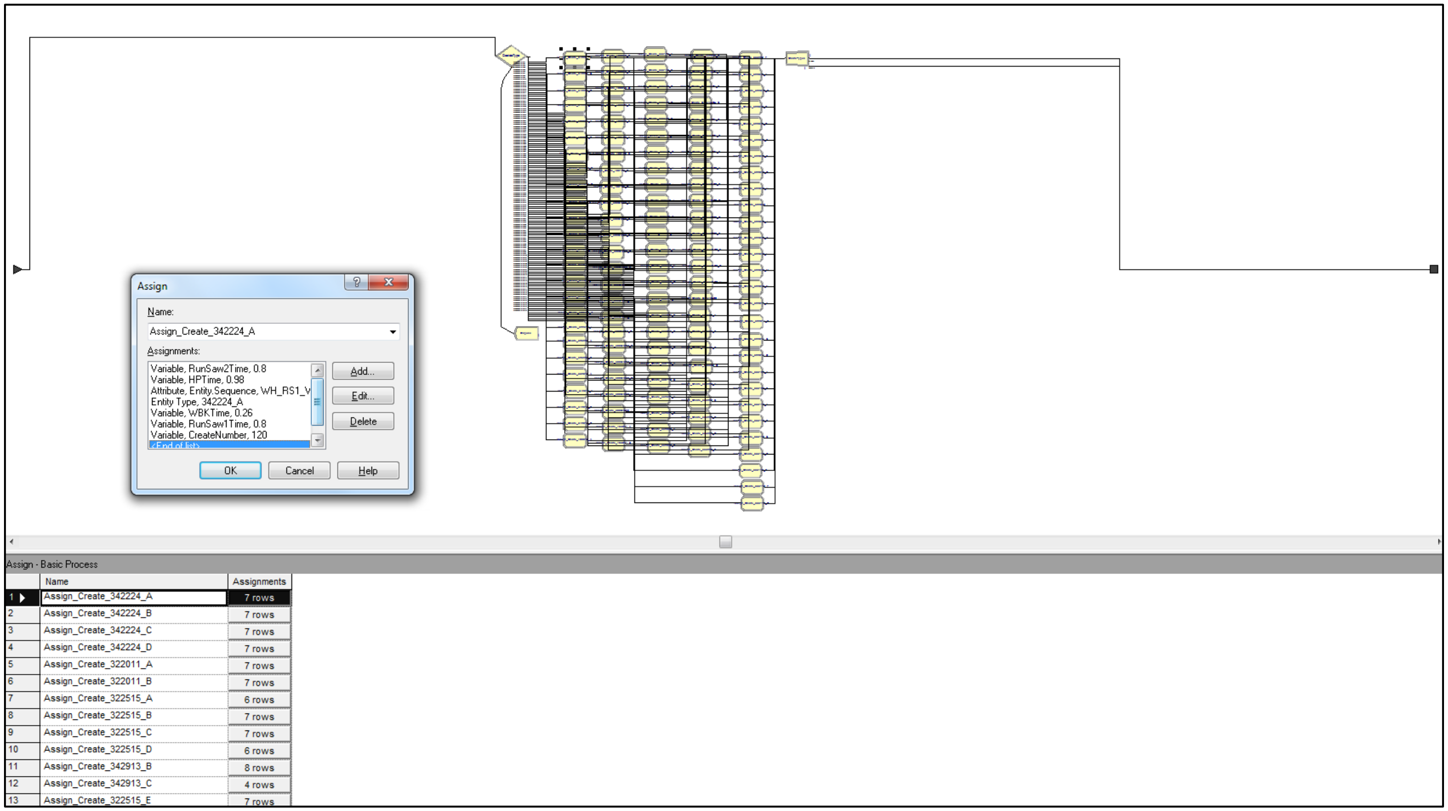
A.4 Batching Inspection



A.5 One-by-one Inspection



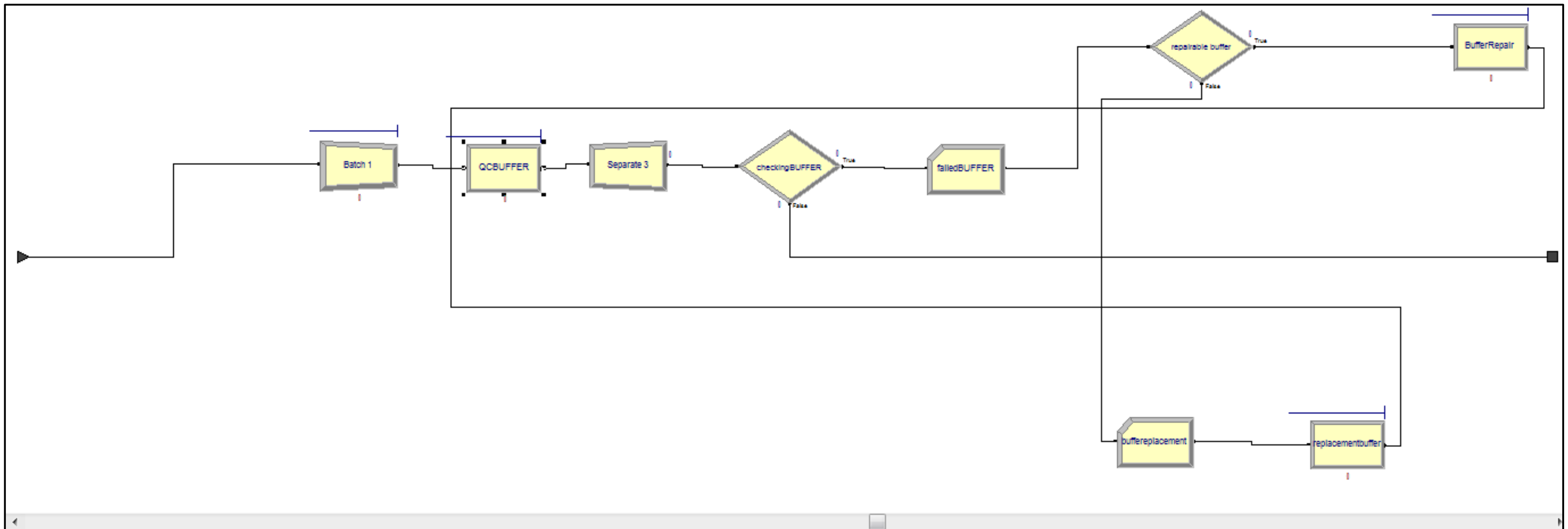
A.6 Assign Modules for each Product Service Time


Assign
Name:
Assign_Create_342224_A
Assignments:
Variable, RunSaw2Time, 0.8
Variable, HPTime, 0.98
Attribute, Entity.Sequence, WH_RS1_V
Entity Type, 342224_A
Variable, WBKTime, 0.26
Variable, RunSaw1Time, 0.8
Variable, CreateNumber, 120
Add...
Edit...
Delete
OK
Cancel
Help
Assign - Basic Process
Name
Assignments
1 Assign_Create_342224_A 7 rows
2 Assign_Create_342224_B 7 rows
3 Assign_Create_342224_C 7 rows
4 Assign_Create_342224_D 7 rows
5 Assign_Create_322011_A 7 rows
6 Assign_Create_322011_B 7 rows
7 Assign_Create_322515_A 6 rows
8 Assign_Create_322515_B 7 rows
9 Assign_Create_322515_C 7 rows
10 Assign_Create_322515_D 6 rows
11 Assign_Create_342913_B 8 rows
12 Assign_Create_342913_C 4 rows
13 Assign_Create_322515_E 7 rows

Appendix B Simulation Inputs

B.1 Buffer Inspection Service Time

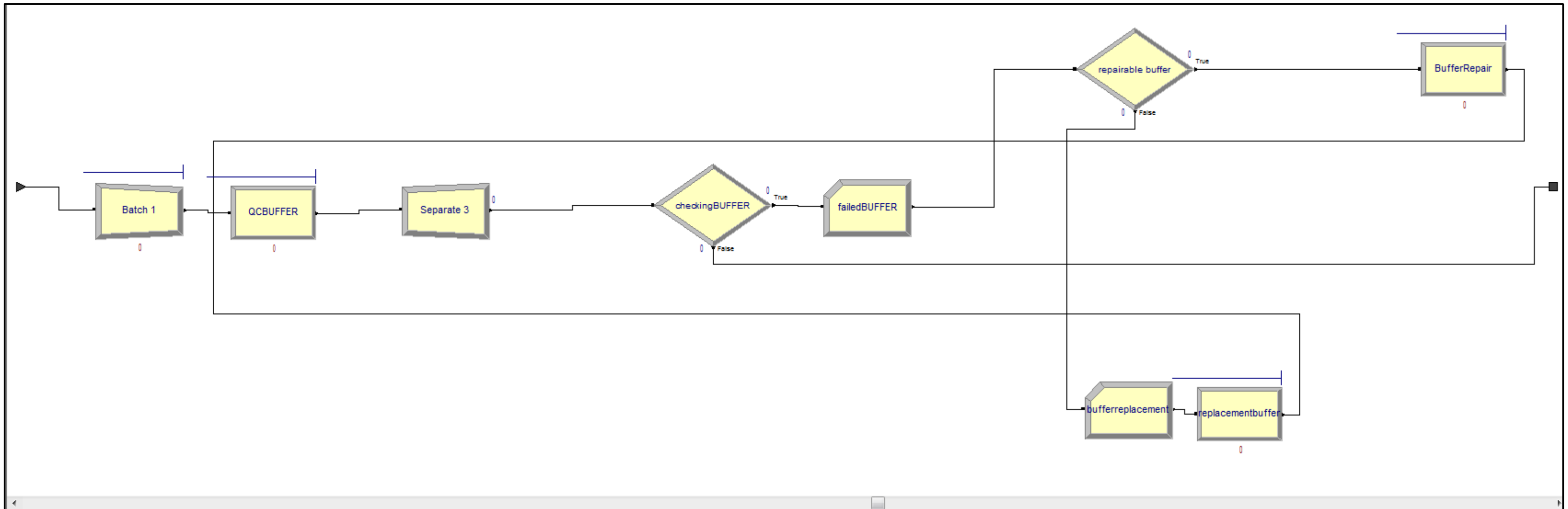
Batch Centralized



Process - Basic Process

	Name	Type	Action	Priority	Resources	Delay Type	Units	Allocation	Minimum	Value	Maximum	Std Dev	Report Statistics
1	QCBUFFER	Standard	Seize Delay Release	Medium(2)	1 rows	Normal	Seconds	Value Added	1	100	2.5	1	☑
2	BufferRepair	Standard	Seize Delay Release	Medium(2)	1 rows	Uniform	Minutes	Value Added	10	1	20	.2	☑
3	replacementbuffer	Standard	Seize Delay Release	Medium(2)	1 rows	Uniform	Minutes	Value Added	20	1	40	.2	☑

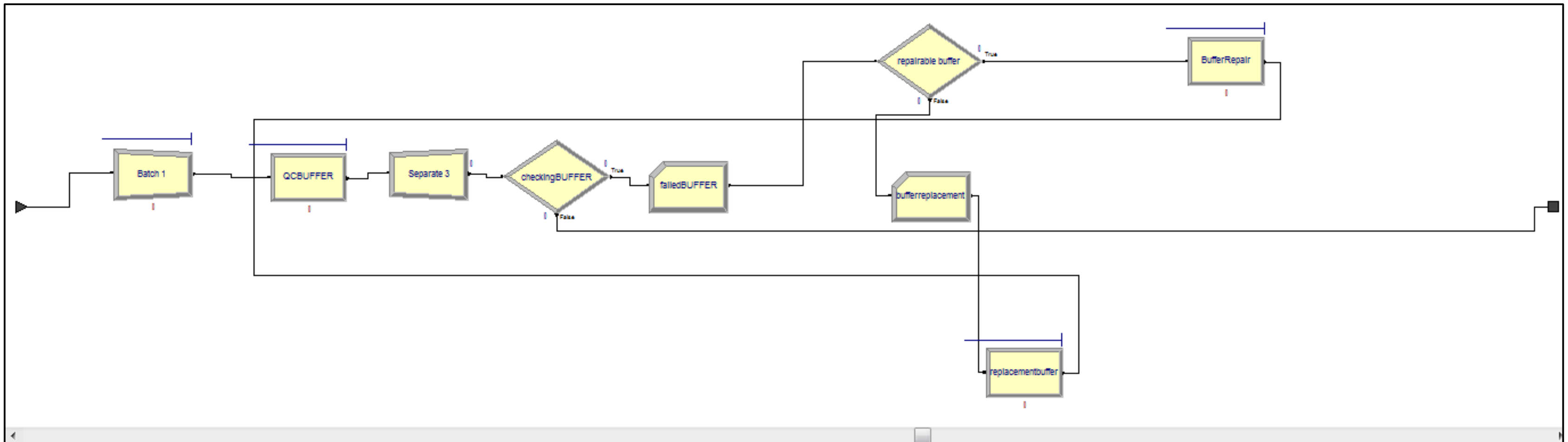
Batch Decentralized



Process - Basic Process

	Name	Type	Action	Priority	Resources	Delay Type	Units	Allocation	Minimum	Value	Maximum	Std Dev	Report Statistics
1	QCBUFFER	Standard	Seize Delay Release	Medium(2)	1 rows	Normal	Seconds	Value Added	1	50	2.5	.5	☑
2	BufferRepair	Standard	Seize Delay Release	Medium(2)	1 rows	Uniform	Minutes	Value Added	5	1	10	.2	☑
3	replacementbuffer	Standard	Seize Delay Release	Medium(2)	1 rows	Uniform	Minutes	Value Added	10	1	20	.2	☑

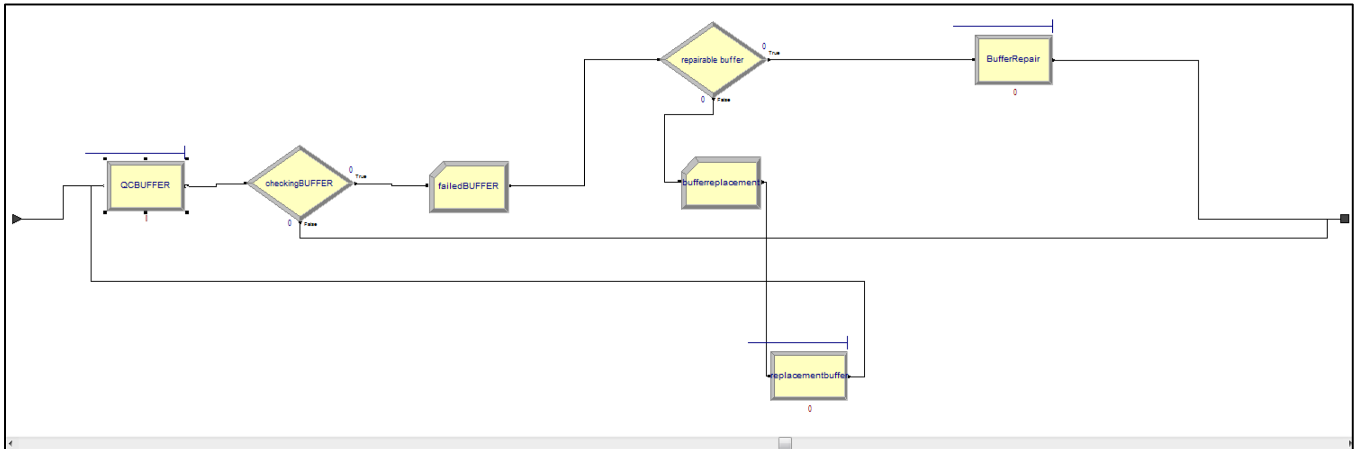
Batch Efficient



Process - Basic Process

	Name	Type	Action	Priority	Resources	Delay Type	Units	Allocation	Minimum	Value	Maximum	Std Dev	Report Statistics
1	QCBUFFER	Standard	Seize Delay Release	Medium(2)	1 rows	Normal	Seconds	Value Added	1	75	2.5	0.75	☑
2	BufferRepair	Standard	Seize Delay Release	Medium(2)	1 rows	Uniform	Minutes	Value Added	5	1	10	.2	☑
3	replacementbuffer	Standard	Seize Delay Release	Medium(2)	1 rows	Uniform	Minutes	Value Added	10	1	20	.2	☑

One-by-one Efficient

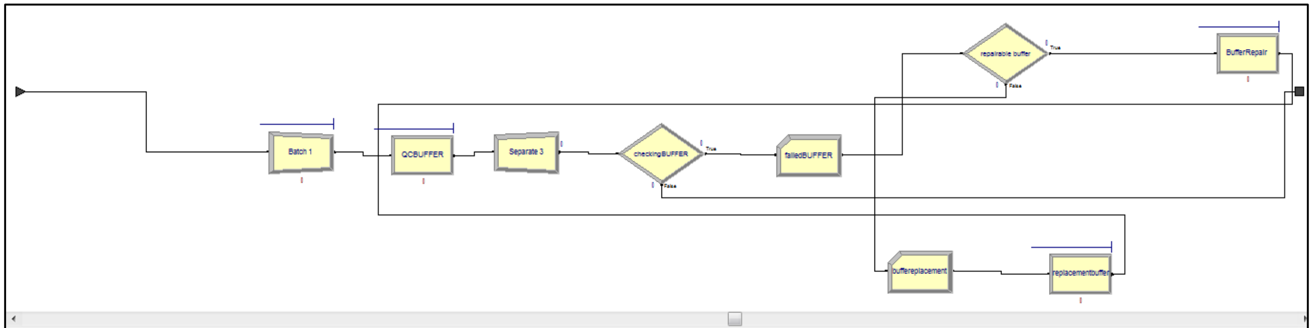


Process - Basic Process

	Name	Type	Action	Priority	Resources	Delay Type	Units	Allocation	Minimum	Value	Maximum	Std Dev	Report Statistics
1	QCBUFFER	Standard	Seize Delay Release	Medium(2)	1 rows	Normal	Seconds	Value Added	1	5	2.5	.05	☑
2	BufferRepair	Standard	Seize Delay Release	Medium(2)	1 rows	Uniform	Minutes	Value Added	5	1	10	.2	☑
3	replacementbuffer	Standard	Seize Delay Release	Medium(2)	1 rows	Uniform	Minutes	Value Added	10	1	20	.2	☑

B.2 Buffer Inspection Decide Modules

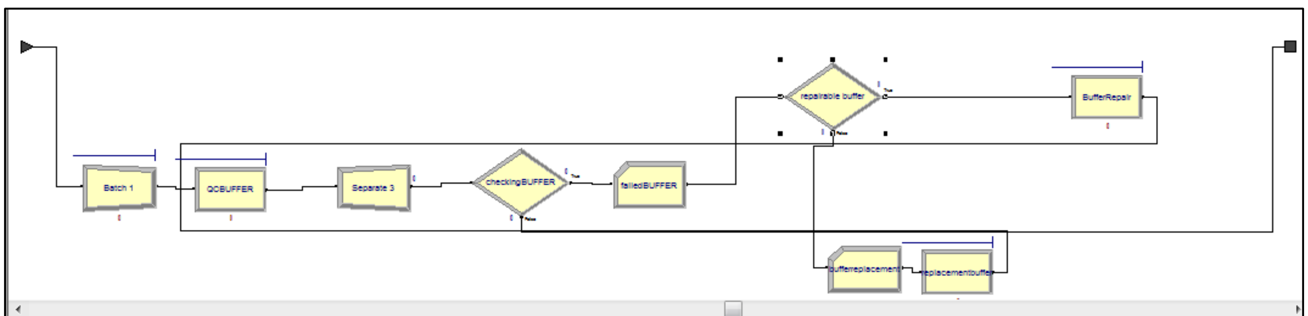
Centralized



Decide - Basic Process

	Name	Type	Percent True
1	checkingBUFFER	2-way by Chance	NORM(9.375,1)
2	repairable buffer	2-way by Chance	NORM(95,1)

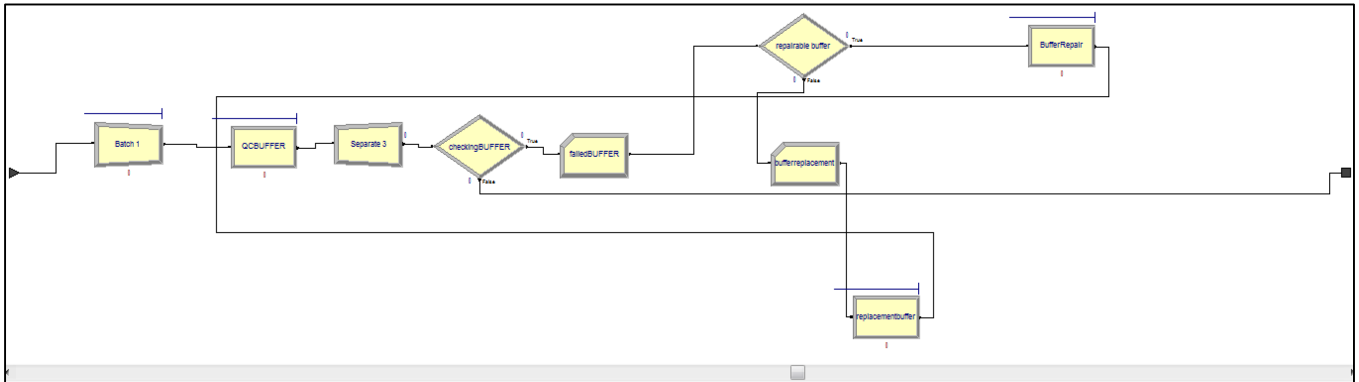
Decentralized



Decide - Basic Process

	Name	Type	Percent True
1	checkingBUFFER	2-way by Chance	NORM(1,0.2)
2	repairable buffer	2-way by Chance	UNIF(97,99)

Efficient



Decide - Basic Process

	Name	Type	Percent True
1	checkingBUFFER	2-way by Chance	NORM(1.2,0.2)
2	repairable buffer	2-way by Chance	UNIF(95,99)

Appendix C Simulation Results

B.1 Preventability Results

2 QC Agents

Batch Efficient V (%)	Batch Decentralized V (%)	One-by-one Efficient V (%)	One-by-one Decentralized V (%)
0.652000	0.564000	0.602837	0.619385
0.633333	0.608333	0.708000	0.670000
0.675048	0.599613	0.658487	0.640082
0.640562	0.562249	0.588235	0.598739
0.667276	0.630713	0.670913	0.677282
0.632432	0.589189	0.651116	0.659229
0.600000	0.612844	0.639831	0.654661
0.653179	0.620424	0.674569	0.625000
0.676083	0.638418	0.674897	0.683128
0.624514	0.585603	0.621444	0.564551
0.615538	0.615538	0.600939	0.640845
0.616667	0.662963	0.683594	0.669922
0.658052	0.588469	0.630290	0.610245
0.683824	0.656250	0.683084	0.584582
0.638672	0.619141	0.640257	0.623126
0.668488	0.659381	0.660044	0.651214
0.659184	0.548980	0.633495	0.548544
0.654971	0.662768	0.682303	0.648188
0.625698	0.638734	0.637002	0.557377
0.662879	0.619318	0.648330	0.652259
0.638835	0.574757	0.643629	0.619870
0.669811	0.607547	0.630769	0.648352
0.632094	0.612524	0.640333	0.582121
0.628405	0.558366	0.691383	0.663327
0.706204	0.585766	0.652655	0.654867
0.654851	0.634328	0.697425	0.577253
0.623274	0.601578	0.610526	0.633684
0.618110	0.561024	0.670757	0.580777
0.687850	0.628037	0.654584	0.603412
0.631474	0.585657	0.678862	0.575203
0.609346	0.618692	0.659184	0.646939
0.676471	0.523109	0.681529	0.632696

0.638037	0.560327	0.652268	0.563715
0.636179	0.563008	0.627615	0.608787
0.656566	0.602020	0.624454	0.617904
0.639279	0.551102	0.635021	0.641350
0.662942	0.633147	0.638249	0.601382
0.594488	0.614173	0.689243	0.675299
0.653061	0.653061	0.638604	0.613963
0.669078	0.609403	0.665306	0.630612
0.665392	0.619503	0.661355	0.587649
0.629278	0.604563	0.676596	0.646809
0.664220	0.618349	0.668750	0.604167
0.646000	0.534000	0.671082	0.624724
0.662214	0.578244	0.663020	0.634573
0.678373	0.617375	0.626697	0.590498
0.643969	0.593385	0.684989	0.606765
0.674200	0.649718	0.665992	0.641700
0.611345	0.565126	0.596950	0.660131
0.662055	0.586957	0.615385	0.584615
0.655804	0.598778	0.605428	0.657620
0.576200	0.572025	0.637168	0.581858
0.658088	0.613971	0.679775	0.659176
0.669776	0.630597	0.622449	0.642857
0.640927	0.666023	0.662474	0.599581
0.589247	0.539785	0.682773	0.644958
0.601961	0.639216	0.625899	0.568345
0.636008	0.614481	0.618138	0.579952
0.633588	0.639313	0.649462	0.617204
0.671785	0.596929	0.698225	0.688363
0.666038	0.620755	0.672727	0.618182
0.637965	0.594912	0.662366	0.595699
0.610075	0.628731	0.672234	0.638831
0.610887	0.588710	0.628450	0.607219
0.622605	0.639847	0.717054	0.643411
0.604555	0.590062	0.616822	0.581776
0.650735	0.641544	0.668182	0.563636
0.620042	0.557411	0.677824	0.638075
0.650558	0.615242	0.611231	0.606911
0.556911	0.599593	0.631929	0.572062
0.630798	0.595547	0.683112	0.635674

0.668571	0.567619	0.657841	0.627291
0.615248	0.654255	0.623608	0.625835
0.615230	0.565130	0.653595	0.605664
0.654369	0.582524	0.569087	0.599532
0.658869	0.606238	0.657505	0.627907
0.656660	0.615385	0.672234	0.609603
0.600000	0.579592	0.658996	0.669456
0.626747	0.620758	0.631579	0.600877
0.633663	0.615842	0.677560	0.581699
0.609375	0.573661	0.595349	0.544186
0.594340	0.596226	0.690229	0.646570
0.706960	0.602564	0.634409	0.647312
0.674858	0.580340	0.669510	0.605544
0.665392	0.630975	0.619154	0.596882
0.645951	0.617702	0.684096	0.612200
0.617761	0.596525	0.691974	0.568330
0.621771	0.614391	0.628998	0.618337
0.633911	0.649326	0.637188	0.594104
0.689013	0.638734	0.619910	0.606335
0.695886	0.645796	0.628337	0.568789
0.681542	0.588235	0.649533	0.553738
0.662162	0.569498	0.644880	0.618736
0.639216	0.647059	0.684564	0.624161
0.634409	0.668459	0.709677	0.627957
0.651852	0.581481	0.646570	0.640333
0.658120	0.675214	0.591324	0.557078
0.658349	0.604607	0.656566	0.701010
0.612903	0.594758	0.656442	0.676892
0.620172	0.596567	0.652838	0.639738

3 QC Agents

Batch Efficient V (%)	Batch Decentralized V (%)	One-by-one Efficient V (%)	One-by-one Decentralized V (%)
0.6240000	0.6160000	0.6276596	0.6106383
0.5937500	0.5937500	0.6512702	0.6466513
0.6595745	0.6015474	0.6973948	0.6332665
0.5963855	0.5783133	0.6625259	0.6418219

0.7001828	0.6489945	0.6735967	0.6133056
0.6774775	0.6234234	0.6124197	0.6338330
0.6513761	0.5981651	0.5916115	0.6158940
0.6724470	0.6069364	0.7280000	0.6520000
0.5951036	0.6252354	0.5776256	0.5981735
0.6322957	0.5603113	0.6508876	0.6548323
0.6235060	0.5876494	0.6808081	0.6626263
0.6518519	0.6111111	0.6263270	0.6008493
0.6282306	0.5626243	0.7068607	0.6444906
0.6672794	0.6452206	0.6601732	0.6428571
0.6289063	0.6640625	0.6781857	0.6501080
0.6047359	0.6575592	0.6587983	0.5836910
0.6285714	0.5918367	0.6419214	0.5960699
0.6120858	0.6023392	0.6799117	0.6048565
0.6182495	0.6573557	0.6449438	0.5842697
0.6420455	0.6212121	0.6410788	0.6244813
0.6349515	0.5980583	0.6794055	0.6305732
0.6566038	0.6433962	0.6101695	0.6610169
0.6418787	0.6203523	0.6599099	0.5630631
0.6906615	0.6459144	0.6373166	0.5870021
0.6350365	0.6131387	0.6748330	0.5857461
0.6641791	0.6119403	0.6753507	0.6533066
0.6252465	0.6173570	0.6701245	0.5954357
0.6673228	0.6161417	0.6168831	0.5995671
0.6523364	0.6280374	0.6343434	0.6505051
0.6095618	0.5956175	0.6732892	0.6048565
0.6336449	0.6411215	0.6466667	0.5844444
0.6134454	0.5861345	0.6386946	0.5990676
0.6523517	0.5623722	0.6361656	0.7058824
0.6138211	0.5914634	0.6477987	0.6331237
0.6444444	0.5797980	0.6343612	0.6013216
0.6312625	0.5230461	0.6639344	0.6004098
0.6815642	0.6256983	0.5853659	0.6274945
0.6279528	0.6535433	0.6535948	0.6122004
0.6753247	0.6679035	0.6813417	0.6352201
0.6347197	0.6184448	0.6177686	0.5826446
0.6921606	0.5831740	0.6808081	0.6222222
0.6159696	0.5893536	0.6321138	0.5995935
0.6678899	0.6018349	0.6348195	0.5774947

0.6220000	0.5700000	0.6483516	0.6505495
0.6679389	0.6183206	0.6468085	0.6340426
0.6192237	0.6414048	0.6348548	0.5580913
0.6517510	0.5875486	0.6788618	0.6402439
0.6854991	0.6139360	0.6557018	0.6381579
0.5882353	0.5399160	0.6923077	0.6237006
0.6620553	0.6067194	0.6365591	0.6150538
0.6048880	0.6456212	0.5876068	0.6282051
0.5720251	0.5469729	0.6742268	0.6268041
0.6672794	0.6470588	0.6113537	0.6353712
0.6361940	0.6156716	0.6728016	0.6421268
0.6100386	0.5965251	0.6217822	0.7188119
0.5870968	0.5935484	0.6377119	0.6822034
0.6745098	0.5941176	0.6200418	0.6492693
0.6438356	0.6242661	0.6342975	0.5909091
0.6736641	0.6068702	0.6913319	0.6236786
0.5911708	0.6276392	0.6000000	0.6387097
0.6603774	0.5735849	0.6502146	0.6051502
0.6360078	0.6692759	0.6544276	0.6673866
0.6212687	0.6324627	0.5673913	0.5913043
0.6048387	0.5524194	0.6331878	0.6441048
0.6551724	0.5977011	0.5976471	0.6611765
0.6190476	0.5859213	0.6860215	0.6387097
0.6525735	0.6691176	0.6465116	0.6209302
0.5824635	0.5574113	0.6806723	0.6953782
0.6431227	0.5427509	0.6738661	0.6479482
0.6117886	0.5670732	0.6540000	0.6420000
0.6586271	0.6382189	0.5982143	0.6272321
0.6190476	0.6038095	0.6694737	0.5978947
0.6223404	0.6276596	0.5956522	0.5782609
0.5771543	0.6152305	0.6720978	0.6130346
0.6796117	0.6038835	0.6545064	0.6094421
0.6179337	0.5925926	0.6373626	0.6263736
0.6716698	0.6097561	0.6713996	0.6206897
0.5897959	0.5816327	0.6610169	0.6165254
0.6447106	0.6007984	0.6837945	0.6976285
0.6336634	0.6475248	0.6821192	0.6225166
0.6205357	0.5647321	0.6569647	0.6299376
0.6603774	0.6490566	0.6222707	0.6506550

0.6520147	0.6465201	0.6323851	0.6673961
0.6313800	0.6162571	0.6428571	0.5959821
0.6787763	0.6845124	0.6465324	0.5525727
0.6854991	0.6233522	0.6226804	0.6597938
0.5772201	0.6138996	0.6976242	0.5658747
0.6697417	0.6088561	0.6796875	0.6738281
0.6127168	0.6300578	0.6087912	0.6219780
0.6331471	0.6126629	0.6406250	0.5892857
0.6726297	0.6493739	0.6125541	0.6385281
0.6206897	0.5557809	0.6752688	0.6279570
0.6525097	0.6138996	0.5894737	0.6105263
0.6745098	0.6294118	0.6142241	0.6142241
0.6756272	0.6487455	0.6792079	0.6217822
0.6629630	0.5740741	0.6803922	0.6235294
0.6803419	0.6341880	0.6441718	0.6012270
0.6506718	0.6871401	0.6644144	0.6441441
0.5625000	0.5524194	0.6572581	0.5907258
0.5965665	0.5665236	0.6406571	0.6406571

4 QC Agents

Batch Efficient V (%)	Batch Decentralized V (%)	One-by-one Efficient V (%)	One-by-one Decentralized V (%)
0.615854	0.581301	0.681342	0.643606
0.670194	0.601411	0.662896	0.590498
0.622824	0.589942	0.621381	0.668151
0.645472	0.605010	0.665298	0.657084
0.690432	0.630394	0.684549	0.622318
0.592292	0.576065	0.660131	0.681917
0.625000	0.601923	0.657778	0.637778
0.647638	0.622047	0.715415	0.652174
0.642185	0.670433	0.644958	0.592437
0.663551	0.603738	0.643016	0.580931
0.701627	0.643761	0.635575	0.629067
0.646617	0.607143	0.660338	0.641350
0.641366	0.597723	0.627660	0.614894
0.648485	0.602020	0.675966	0.603004
0.654412	0.648897	0.664502	0.660173
0.667347	0.593878	0.682377	0.641393

0.659851	0.596654	0.602771	0.595843
0.656772	0.602968	0.641138	0.599562
0.634000	0.578000	0.613821	0.595528
0.662900	0.642185	0.652632	0.635789
0.686679	0.617261	0.665966	0.630252
0.615546	0.596639	0.641593	0.632743
0.669216	0.642447	0.633891	0.619247
0.684502	0.608856	0.678000	0.666000
0.661232	0.617754	0.699387	0.605317
0.643969	0.610895	0.602222	0.644444
0.644359	0.604207	0.642857	0.597959
0.669811	0.620755	0.666667	0.672802
0.657303	0.593633	0.655391	0.649049
0.630435	0.648221	0.687627	0.647059
0.626459	0.603113	0.614880	0.608315
0.696203	0.531646	0.594360	0.624729
0.623218	0.576375	0.684902	0.571116
0.641732	0.618110	0.642570	0.632530
0.625514	0.594650	0.635776	0.614224
0.624060	0.588346	0.680894	0.617886
0.662813	0.585742	0.671674	0.630901
0.639469	0.609108	0.630928	0.608247
0.685393	0.621723	0.636166	0.579521
0.633947	0.578732	0.652778	0.644841
0.692929	0.561616	0.692615	0.614770
0.586614	0.588583	0.600907	0.612245
0.659091	0.594697	0.659619	0.627907
0.672447	0.603083	0.621444	0.599562
0.657795	0.640684	0.690987	0.643777
0.631692	0.550321	0.674944	0.528217
0.633745	0.580247	0.625821	0.621444
0.689013	0.627561	0.662526	0.639752
0.653021	0.633528	0.683742	0.576837
0.632735	0.616766	0.648033	0.672878
0.645522	0.606343	0.691983	0.609705
0.616364	0.609091	0.651805	0.649682
0.682171	0.633721	0.543735	0.567376
0.567391	0.573913	0.672646	0.627803
0.652751	0.626186	0.686391	0.672584

0.607477	0.577570	0.670282	0.633406
0.704830	0.604651	0.658174	0.569002
0.622430	0.579439	0.657447	0.634043
0.653772	0.618956	0.639723	0.591224
0.657534	0.602740	0.681913	0.638254
0.609037	0.593320	0.637317	0.631027
0.625731	0.623782	0.599567	0.642857
0.607803	0.599589	0.637895	0.597895
0.647969	0.615087	0.679570	0.604301
0.715044	0.640708	0.688109	0.637427
0.673179	0.646536	0.665158	0.606335
0.619835	0.557851	0.641548	0.604888
0.643810	0.609524	0.714885	0.645702
0.622824	0.603482	0.654737	0.633684
0.590476	0.609524	0.624190	0.591793
0.588235	0.613725	0.648707	0.625000
0.642570	0.590361	0.653333	0.642222
0.671454	0.640934	0.647917	0.616667
0.635135	0.619691	0.658436	0.576132
0.658777	0.585799	0.669276	0.657534
0.688679	0.615094	0.552402	0.582969
0.652928	0.535792	0.664016	0.634195
0.608187	0.592593	0.642082	0.626898
0.677643	0.684575	0.648325	0.535885
0.623782	0.629630	0.713740	0.673664
0.623742	0.595573	0.655481	0.635347
0.634578	0.618861	0.650099	0.622266
0.636743	0.607516	0.651982	0.627753
0.599593	0.581301	0.648374	0.634146
0.647969	0.622824	0.641084	0.609481
0.675000	0.613462	0.642058	0.630872
0.629423	0.616387	0.674468	0.621277
0.598058	0.588350	0.646316	0.650526
0.675299	0.549801	0.666667	0.660569
0.596708	0.574074	0.628099	0.613636
0.662385	0.644037	0.636364	0.614719
0.619658	0.551282	0.660907	0.606911
0.692308	0.655678	0.666667	0.579521
0.613108	0.598309	0.651111	0.571111

0.611440	0.562130	0.698795	0.670683
0.617357	0.603550	0.678652	0.588764
0.602637	0.625235	0.616740	0.561674
0.654851	0.639925	0.658228	0.628692
0.629981	0.554080	0.630588	0.595294
0.613360	0.641700	0.707424	0.606987

B.2 Reliability Results

2 QC Agents

Batch Efficient R (%)	Batch Decentralized R (%)	Batch Centralized R (%)	One-by-one Efficient R (%)	One-by-one Decentralized R (%)	One-by-on Centralized R (%)
0.9984	0.9988	0.997	0.9978	0.9976	0.9956
0.9984	0.9972	0.9972	0.998	0.9984	0.9962
0.9964	0.999	0.997	0.9978	0.9964	0.9972
0.9974	0.998	0.9982	0.999	0.998	0.9972
0.9978	0.9982	0.9972	0.9974	0.999	0.9978
0.9976	0.9976	0.998	0.999	0.9974	0.9968
0.9978	0.9986	0.9946	0.9974	0.998	0.998
0.997	0.9978	0.9972	0.9978	0.9984	0.9972
0.9986	0.997	0.996	0.999	0.9988	0.9972
0.9984	0.9978	0.9972	0.9974	0.998	0.998
0.9976	0.9976	0.996	0.998	1	0.9968
0.9976	0.9986	0.9962	0.997	0.9984	0.9974
0.998	0.9984	0.996	0.9984	0.9984	0.9962
0.9974	0.9988	0.9984	0.9982	0.9982	0.9972
0.9978	0.998	0.9968	0.9964	0.9982	0.9976
0.9974	0.9984	0.9968	0.9968	0.998	0.9974
0.9978	0.9984	0.998	0.9974	0.9976	0.9976
0.9982	0.9986	0.997	0.998	0.9984	0.9976
0.998	0.9984	0.9978	0.9984	0.9982	0.9966
0.9968	0.9986	0.9976	0.9972	0.9984	0.9982
0.9984	0.9976	0.996	0.9976	0.9976	0.9978
0.9962	0.997	0.9972	0.9978	0.9984	0.9976
0.9984	0.999	0.9966	0.9974	0.9972	0.9966
0.9984	0.9982	0.9976	0.9972	0.998	0.996

0.998	0.999	0.997	0.9974	0.9984	0.997
0.9978	0.9958	0.9968	0.9978	0.9986	0.9952
0.9968	0.9982	0.9966	0.9972	0.9976	0.9966
0.9982	0.9982	0.9976	0.9982	0.9986	0.9962
0.9976	0.998	0.998	0.9976	0.9984	0.998
0.9978	0.9982	0.9976	0.997	0.998	0.9966
0.9972	0.998	0.9976	0.9976	0.9968	0.9974
0.9978	0.9988	0.9976	0.9986	0.998	0.9978
0.9972	0.9984	0.9958	0.997	0.9982	0.9974
0.9968	0.997	0.9974	0.9968	0.9976	0.9974
0.9968	0.998	0.9974	0.997	0.9968	0.9964
0.9968	0.998	0.9974	0.9968	0.9982	0.9966
0.9988	0.9984	0.9968	0.997	0.998	0.9966
0.9976	0.9978	0.9964	0.9948	0.998	0.9968
0.9962	0.9972	0.9964	0.9972	0.998	0.9974
0.9974	0.9978	0.9988	0.9974	0.9982	0.9978
0.9974	0.9986	0.9976	0.998	0.9986	0.998
0.9964	0.9966	0.9966	0.9974	0.9972	0.9968
0.9972	0.9984	0.9968	0.9976	0.9982	0.9974
0.9968	0.9984	0.9954	0.9974	0.9968	0.9956
0.9986	0.9984	0.9958	0.9976	0.9986	0.9974
0.9974	0.9976	0.9968	0.9974	0.9984	0.9964
0.9976	0.9968	0.9966	0.9972	0.9976	0.9962
0.9982	0.9988	0.9978	0.9982	0.9968	0.9972
0.9984	0.9962	0.9976	0.9966	0.9968	0.9976
0.9976	0.9986	0.9968	0.9976	0.9988	0.9966
0.998	0.9988	0.9962	0.998	0.9986	0.9968
0.998	0.9976	0.9952	0.9976	0.9978	0.9978
0.9984	0.9978	0.9974	0.9984	0.9986	0.998
0.997	0.9978	0.9966	0.9978	0.9968	0.9964
0.998	0.9982	0.9964	0.9988	0.998	0.9978
0.9972	0.9972	0.9972	0.9976	0.9986	0.9978
0.998	0.999	0.9978	0.9976	0.9982	0.9966
0.9978	0.9982	0.9962	0.9978	0.9974	0.9956
0.9974	0.9984	0.9978	0.9974	0.9982	0.997
0.9986	0.9974	0.9968	0.9984	0.9972	0.9966
0.9974	0.997	0.997	0.9982	0.998	0.9972
0.997	0.9978	0.9972	0.9974	0.9974	0.9972
0.9974	0.9988	0.9968	0.998	0.9972	0.9964

0.999	0.9972	0.9972	0.9974	0.9982	0.9982
0.9974	0.9974	0.997	0.9968	0.9978	0.996
0.9976	0.9972	0.9962	0.9978	0.997	0.9978
0.997	0.9976	0.9972	0.998	0.9988	0.9968
0.9988	0.9988	0.996	0.997	0.9984	0.9968
0.996	0.9966	0.9976	0.9976	0.9986	0.9948
0.9982	0.9974	0.9964	0.9994	0.9974	0.9976
0.9978	0.9984	0.9966	0.998	0.9978	0.998
0.9966	0.9972	0.9972	0.998	0.9976	0.9976
0.9964	0.9984	0.9974	0.998	0.9976	0.9976
0.9964	0.9972	0.9968	0.9986	0.9982	0.9978
0.998	0.998	0.9982	0.9972	0.9978	0.998
0.9974	0.9986	0.9966	0.9978	0.9976	0.9966
0.9982	0.9974	0.9974	0.9968	0.9974	0.9976
0.9972	0.9974	0.9966	0.9982	0.9976	0.9966
0.9974	0.9976	0.9972	0.9984	0.9978	0.9972
0.9986	0.9974	0.9966	0.9984	0.9986	0.998
0.9984	0.9986	0.9972	0.9972	0.9982	0.9958
0.9992	0.999	0.9972	0.997	0.998	0.9974
0.9972	0.9992	0.9968	0.9982	0.9976	0.9982
0.998	0.9968	0.9972	0.9974	0.9966	0.9982
0.9978	0.998	0.998	0.9984	0.998	0.9974
0.9976	0.9978	0.998	0.9976	0.9986	0.997
0.9972	0.9982	0.9964	0.9976	0.9978	0.9972
0.9976	0.9974	0.9976	0.9978	0.998	0.9956
0.9982	0.9984	0.9974	0.9972	0.9976	0.997
0.9976	0.9978	0.996	0.997	0.998	0.9982
0.9988	0.9982	0.9978	0.997	0.998	0.9974
0.9982	0.9984	0.9976	0.998	0.9994	0.9978
0.9982	0.9982	0.9972	0.9972	0.998	0.9972
0.9986	0.998	0.9968	0.9962	0.9978	0.9974
0.9976	0.9978	0.9972	0.9976	0.9974	0.9972
0.9976	0.998	0.9972	0.9982	0.998	0.9974
0.9968	0.9988	0.9976	0.9978	0.9984	0.9976
0.998	0.9978	0.9968	0.9974	0.9986	0.9984
0.9978	0.9978	0.9964	0.9984	0.9984	0.9974
0.998	0.9968	0.9984	0.9976	0.998	0.9976

3 QC Agents

Batch Efficient R (%)	Batch Decentralized R (%)	Batch Centralized R (%)	One-by-one Efficient R (%)	One-by-one Decentralized R (%)	One-by-on Centralized R (%)
0.9968	0.9992	0.997	0.9982	0.999	0.9988
0.9982	0.9976	0.9972	0.997	0.9976	0.9966
0.9968	0.9986	0.997	0.9988	0.999	0.9976
0.9976	0.9972	0.9982	0.998	0.9982	0.997
0.9978	0.9984	0.9972	0.9976	0.999	0.9976
0.9972	0.9976	0.998	0.9978	0.9982	0.9962
0.9974	0.9972	0.9946	0.9982	0.9986	0.9968
0.9968	0.9982	0.9972	0.9982	0.999	0.9974
0.9976	0.9976	0.996	0.9976	0.9978	0.9966
0.9984	0.9984	0.9972	0.9982	0.9984	0.998
0.9962	0.9982	0.996	0.998	0.9986	0.9966
0.9976	0.9984	0.9962	0.9982	0.9982	0.996
0.9964	0.998	0.996	0.997	0.9982	0.997
0.9976	0.9984	0.9984	0.9978	0.9984	0.9972
0.9972	0.9978	0.9968	0.998	0.9986	0.9976
0.9972	0.9972	0.9968	0.9976	0.9982	0.9976
0.9978	0.9974	0.998	0.9972	0.9974	0.9966
0.9988	0.9988	0.997	0.999	0.9986	0.9982
0.998	0.9978	0.9978	0.9964	0.9982	0.9972
0.998	0.9978	0.9976	0.9972	0.9974	0.998
0.9972	0.9988	0.996	0.9974	0.9986	0.996
0.9988	0.9976	0.9972	0.998	0.999	0.9976
0.9988	0.9982	0.9966	0.9988	0.9986	0.9968
0.998	0.998	0.9976	0.9986	0.9984	0.9962
0.9978	0.9982	0.997	0.9976	0.999	0.997
0.9976	0.998	0.9968	0.998	0.9974	0.9972
0.9976	0.9978	0.9966	0.9976	0.9976	0.998
0.9978	0.999	0.9976	0.9978	0.9978	0.9958
0.9968	0.9986	0.998	0.9978	0.9992	0.9972
0.9974	0.9982	0.9976	0.9972	0.998	0.9962
0.9968	0.9988	0.9976	0.9976	0.9968	0.996
0.9976	0.9976	0.9976	0.9982	0.9986	0.9978
0.9978	0.9988	0.9958	0.9974	0.9978	0.9978
0.997	0.9974	0.9974	0.9978	0.9966	0.9956
0.9978	0.9978	0.9974	0.9968	0.9986	0.9964
0.997	0.9986	0.9974	0.9974	0.9984	0.9948

0.9962	0.9976	0.9968	0.996	0.9984	0.9982
0.9986	0.9982	0.9964	0.9976	0.9982	0.9982
0.9976	0.999	0.9964	0.9964	0.998	0.996
0.9962	0.9976	0.9988	0.996	0.9986	0.9964
0.9976	0.9974	0.9976	0.9972	0.9992	0.9956
0.9972	0.9976	0.9966	0.998	0.9974	0.9978
0.9978	0.9974	0.9968	0.9962	0.9982	0.9974
0.9974	0.9988	0.9954	0.9976	0.9984	0.9978
0.9976	0.9978	0.9958	0.9982	0.9972	0.9966
0.9982	0.9986	0.9968	0.9974	0.9976	0.9982
0.9988	0.9988	0.9966	0.9986	0.9976	0.9968
0.9982	0.9974	0.9978	0.9972	0.9982	0.9972
0.999	0.997	0.9976	0.998	0.9978	0.9976
0.9978	0.9974	0.9968	0.9982	0.9984	0.9964
0.9984	0.9972	0.9962	0.9982	0.9982	0.9958
0.998	0.9986	0.9952	0.9972	0.997	0.996
0.9976	0.9978	0.9974	0.9978	0.9986	0.996
0.9974	0.9976	0.9966	0.997	0.9988	0.9968
0.9978	0.9976	0.9964	0.9976	0.9972	0.9968
0.998	0.9992	0.9972	0.9982	0.9976	0.997
0.9986	0.9982	0.9978	0.998	0.9982	0.9978
0.9974	0.998	0.9962	0.998	0.998	0.9964
0.9978	0.9984	0.9978	0.9972	0.9984	0.998
0.9962	0.998	0.9968	0.997	0.9986	0.9962
0.9962	0.9976	0.997	0.997	0.9974	0.9966
0.9986	0.9978	0.9972	0.9978	0.9976	0.9972
0.9986	0.9982	0.9968	0.9982	0.9986	0.9964
0.9972	0.9984	0.9972	0.9976	0.9982	0.9974
0.9982	0.9994	0.997	0.9974	0.998	0.9972
0.997	0.9972	0.9962	0.997	0.998	0.9966
0.9966	0.9986	0.9972	0.9974	0.9974	0.9978
0.9964	0.9982	0.996	0.9976	0.9976	0.9962
0.9974	0.9988	0.9976	0.9948	0.9978	0.9954
0.9978	0.9978	0.9964	0.9972	0.9976	0.9974
0.9988	0.9978	0.9966	0.9984	0.9974	0.9974
0.9972	0.9976	0.9972	0.9968	0.9978	0.995
0.997	0.9978	0.9974	0.9972	0.9976	0.9968
0.999	0.9982	0.9968	0.9972	0.9984	0.9968
0.9974	0.9984	0.9982	0.9982	0.9976	0.9974

0.9982	0.9988	0.9966	0.9992	0.9976	0.9976
0.9972	0.9986	0.9974	0.9982	0.9968	0.9964
0.9986	0.998	0.9966	0.9994	0.9984	0.9974
0.9974	0.9974	0.9972	0.998	0.9982	0.997
0.9978	0.9986	0.9966	0.9974	0.9978	0.997
0.9984	0.9986	0.9972	0.997	0.9988	0.9964
0.998	0.9982	0.9972	0.9966	0.9984	0.9972
0.9984	0.9984	0.9968	0.9982	0.9986	0.9978
0.9962	0.999	0.9972	0.9982	0.9976	0.997
0.9986	0.9988	0.998	0.9976	0.9976	0.9972
0.9984	0.9984	0.998	0.9986	0.998	0.998
0.9974	0.9986	0.9964	0.9972	0.9976	0.997
0.9974	0.9974	0.9976	0.997	0.9978	0.9974
0.9992	0.9976	0.9974	0.997	0.9974	0.9964
0.9978	0.9986	0.996	0.9984	0.9982	0.9976
0.997	0.9978	0.9978	0.9978	0.9976	0.9968
0.9986	0.9984	0.9976	0.9978	0.9974	0.9982
0.9976	0.9974	0.9972	0.9982	0.9976	0.9972
0.9976	0.9984	0.9968	0.9984	0.9986	0.9956
0.9964	0.998	0.9972	0.997	0.9974	0.9976
0.9986	0.9972	0.9972	0.9986	0.9984	0.9962
0.9976	0.9982	0.9976	0.998	0.999	0.9966
0.9984	0.9986	0.9968	0.997	0.9984	0.997
0.9968	0.9978	0.9964	0.9978	0.998	0.997
0.9956	0.9982	0.9984	0.9972	0.9974	0.996

4 QC Agents

Batch Efficient R (%)	Batch Decentralized R (%)	Batch Centralized R (%)	One-by-one Efficient R (%)	One-by-one Decentralized R (%)	One-by-on Centralized R (%)
0.998	0.9974	0.9958	0.998	0.9988	0.9968
0.9972	0.9988	0.9966	0.998	0.9984	0.9968
0.9982	0.999	0.9962	0.9982	0.9964	0.998
0.9978	0.9982	0.9958	0.9966	0.9976	0.998
0.9988	0.9986	0.9982	0.9966	0.9992	0.9972
0.9966	0.9994	0.9966	0.9976	0.9978	0.9984
0.9976	0.9988	0.9976	0.9972	0.9976	0.9968
0.9968	0.9978	0.9972	0.9976	0.9978	0.9982
0.9972	0.9998	0.9964	0.998	0.9986	0.998

0.9968	0.9982	0.997	0.9976	0.998	0.9972
0.9986	0.9974	0.9974	0.9974	0.998	0.9978
0.9964	0.998	0.997	0.9978	0.9976	0.997
0.9978	0.9982	0.9966	0.9974	0.9974	0.9974
0.9984	0.998	0.9974	0.9972	0.9984	0.997
0.9986	0.998	0.9982	0.9966	0.9976	0.9978
0.996	0.9958	0.9972	0.998	0.9994	0.9968
0.9974	0.9986	0.997	0.9984	0.9988	0.9968
0.998	0.9982	0.9972	0.9974	0.9974	0.9976
0.9982	0.9996	0.9976	0.9978	0.998	0.997
0.9976	0.9982	0.9964	0.9978	0.9988	0.9978
0.998	0.9974	0.9986	0.997	0.9968	0.998
0.998	0.9982	0.9974	0.9976	0.999	0.9968
0.996	0.9978	0.9964	0.9972	0.9982	0.9962
0.9976	0.9976	0.9968	0.998	0.9978	0.9968
0.998	0.998	0.9966	0.9974	0.9978	0.9976
0.999	0.9984	0.9968	0.9984	0.9988	0.996
0.997	0.9982	0.9962	0.9974	0.9984	0.9958
0.9986	0.9982	0.9978	0.9972	0.9974	0.9982
0.9968	0.9972	0.997	0.9986	0.9984	0.998
0.999	0.9984	0.9972	0.9966	0.9978	0.9964
0.9982	0.997	0.9974	0.9966	0.997	0.9976
0.997	0.9966	0.9974	0.997	0.9982	0.9968
0.9972	0.9984	0.9956	0.9974	0.9982	0.997
0.9978	0.9966	0.9978	0.9982	0.998	0.9964
0.9988	0.9982	0.997	0.9984	0.998	0.9972
0.9974	0.9968	0.997	0.9976	0.998	0.996
0.998	0.998	0.9968	0.9968	0.9982	0.997
0.998	0.9976	0.9974	0.9976	0.9976	0.9966
0.9958	0.9982	0.9964	0.997	0.9986	0.9968
0.9968	0.9992	0.9966	0.9982	0.9982	0.9982
0.9968	0.999	0.9966	0.9958	0.9984	0.9964
0.997	0.999	0.9954	0.9958	0.9976	0.996
0.9976	0.9988	0.996	0.9974	0.9978	0.996
0.9986	0.998	0.9966	0.9976	0.9976	0.9974
0.9964	0.9982	0.996	0.9964	0.9974	0.998
0.9976	0.9984	0.9966	0.9962	0.997	0.9974
0.9974	0.9968	0.997	0.9972	0.9988	0.9966
0.998	0.9982	0.9966	0.998	0.9974	0.9968

0.998	0.9976	0.9978	0.999	0.9976	0.9974
0.9982	0.9976	0.9968	0.9984	0.998	0.9968
0.9978	0.9976	0.9974	0.9976	0.998	0.9974
0.9976	0.998	0.9974	0.998	0.997	0.9964
0.997	0.9974	0.9968	0.9986	0.9968	0.9976
0.9976	0.9978	0.9966	0.9974	0.9978	0.9974
0.998	0.998	0.9968	0.9982	0.9968	0.9974
0.998	0.9982	0.997	0.9972	0.9978	0.996
0.9962	0.9982	0.9984	0.9982	0.9986	0.9956
0.9962	0.9986	0.9968	0.9972	0.9982	0.9966
0.9962	0.9974	0.9964	0.9988	0.9974	0.997
0.997	0.9982	0.997	0.997	0.998	0.998
0.9974	0.9984	0.9988	0.9966	0.9978	0.9964
0.9978	0.9974	0.9982	0.9982	0.9974	0.9976
0.9978	0.9988	0.9978	0.9974	0.9974	0.9982
0.9976	0.9982	0.9968	0.9984	0.998	0.9978
0.9974	0.9986	0.998	0.998	0.9982	0.9966
0.9966	0.9982	0.9968	0.9984	0.9982	0.9966
0.997	0.9986	0.997	0.9984	0.997	0.9954
0.9972	0.9972	0.997	0.9978	0.9982	0.9972
0.9978	0.9974	0.9974	0.9954	0.9988	0.9976
0.9976	0.9978	0.9962	0.9974	0.9986	0.9958
0.998	0.9978	0.9972	0.998	0.9986	0.997
0.9974	0.998	0.996	0.9972	0.9972	0.9974
0.998	0.9974	0.996	0.997	0.9968	0.997
0.997	0.9976	0.9978	0.9974	0.998	0.9956
0.9974	0.9982	0.9966	0.9976	0.9974	0.9972
0.9976	0.9988	0.9968	0.997	0.9984	0.996
0.9976	0.9978	0.9968	0.9978	0.9978	0.998
0.9978	0.9978	0.9952	0.998	0.9966	0.9972
0.9982	0.9984	0.9956	0.997	0.9972	0.9966
0.9982	0.9992	0.996	0.9968	0.9986	0.996
0.9988	0.9984	0.9962	0.997	0.9988	0.9964
0.998	0.998	0.9968	0.9982	0.9988	0.9964
0.9976	0.9968	0.9962	0.9978	0.998	0.9966
0.9968	0.998	0.9962	0.9982	0.9972	0.9966
0.9972	0.9982	0.9976	0.998	0.9986	0.997
0.9984	0.9974	0.997	0.9976	0.9984	0.997
0.9952	0.9978	0.997	0.9972	0.9976	0.996

0.9976	0.9978	0.9978	0.9986	0.9978	0.997
0.9982	0.9986	0.9988	0.9974	0.998	0.9968
0.9978	0.9984	0.9978	0.998	0.9988	0.9982
0.999	0.9984	0.9966	0.9978	0.9982	0.9972
0.9982	0.998	0.997	0.9984	0.9986	0.9982
0.9972	0.998	0.9968	0.9966	0.998	0.9974
0.9982	0.9978	0.9956	0.9982	0.9978	0.9968
0.998	0.9982	0.9968	0.9974	0.9974	0.9974
0.9976	0.9978	0.9978	0.9968	0.9982	0.9962
0.9978	0.998	0.9978	0.9968	0.9972	0.998
0.998	0.998	0.9974	0.997	0.9974	0.9972
0.9976	0.997	0.996	0.9976	0.9982	0.997
0.999	0.9976	0.9966	0.9982	0.9982	0.9964

B.3 Time Completion Results

2 QC Agents

Batch Efficient TTC (hrs)	Batch Decentralized TTC (hrs)	Batch Centralized TTC (hrs)	One-by-one Efficient TTC (hrs)	One-by-one Decentralized TTC (hrs)	One-by-on Centralized TTC (hrs)
81.315	72.274	81.594	67.636	72.919	67.773
77.794	70.572	80.225	67.629	73.285	68.028
79.699	70.139	81.163	67.577	73.161	66.525
79.798	69.997	83.094	67.674	73.406	68.114
76.986	69.784	80.777	67.358	72.203	68.157
79.996	71.374	81.053	67.672	72.920	66.782
80.465	69.850	81.770	67.288	72.373	66.154
81.277	73.030	81.840	68.018	73.147	68.559
79.692	71.374	82.721	66.571	72.119	67.134
78.345	69.212	81.372	68.001	73.483	67.982
77.988	69.978	80.584	68.558	72.473	65.821
78.170	69.502	81.204	69.858	73.304	66.236
79.183	71.136	80.419	68.251	72.608	66.836
80.343	71.592	81.144	67.376	73.276	67.464
79.112	73.475	81.155	67.192	73.346	67.081
79.539	69.909	80.890	67.355	72.390	66.451
80.269	71.048	81.625	67.825	71.652	68.838
78.957	69.558	79.653	67.372	73.267	65.928
78.244	72.197	80.033	67.473	73.599	66.944

79.234	71.585	81.222	67.379	72.304	67.177
81.480	71.077	82.191	68.097	72.417	66.431
79.550	74.074	81.815	66.582	72.020	66.255
78.139	70.821	80.937	67.931	73.036	67.116
79.849	72.060	82.221	67.357	72.527	66.687
79.604	70.707	81.140	67.455	72.225	67.163
80.471	70.838	80.144	67.450	73.069	67.175
81.601	69.569	80.112	67.588	72.928	66.753
80.136	69.410	81.100	66.695	72.701	67.534
79.433	70.906	81.756	66.125	73.084	66.492
79.180	70.658	77.692	66.867	72.688	67.196
78.879	69.813	79.736	67.303	72.742	67.160
81.637	68.895	82.832	67.517	73.473	68.912
81.989	70.009	80.094	67.606	72.387	66.138
79.756	69.220	81.487	67.663	73.692	66.779
77.514	69.566	81.203	68.217	73.185	66.716
81.157	71.819	82.767	68.204	73.400	67.438
78.450	72.064	80.044	67.493	72.690	67.375
78.055	72.181	80.376	68.170	71.887	67.884
78.915	70.140	80.482	68.652	73.510	66.162
77.719	70.668	81.185	67.162	72.791	67.243
78.486	72.980	80.239	68.680	73.240	67.454
80.011	70.762	81.617	66.528	72.360	66.933
79.427	69.676	82.768	68.581	73.240	66.415
78.183	70.808	80.078	67.697	73.469	68.999
78.944	70.100	81.079	68.121	72.408	66.845
79.934	71.726	81.753	68.210	72.635	67.425
79.934	71.380	82.706	67.068	73.089	66.471
81.613	69.942	82.131	68.042	72.903	67.046
79.726	71.011	80.074	67.195	72.130	67.765
77.800	70.163	80.652	68.170	73.101	66.660
78.722	73.102	82.264	67.114	72.879	65.103
79.411	71.989	80.862	67.376	72.215	67.348
79.838	72.576	82.271	67.970	73.127	66.394
79.626	69.487	82.058	68.167	73.132	66.574
81.313	71.411	81.383	67.620	72.882	66.776
78.922	70.928	81.622	67.426	72.362	66.478
80.233	71.720	81.316	67.665	72.447	67.283
80.450	71.013	80.864	69.313	72.725	66.635

80.452	71.843	81.962	67.443	72.487	68.523
79.254	70.390	81.629	67.476	73.487	66.638
78.426	70.593	79.028	67.872	72.253	66.825
81.277	72.652	81.799	67.870	72.163	67.283
80.495	69.336	81.762	67.948	72.835	67.866
76.727	68.206	83.160	68.256	72.841	66.123
80.055	69.645	81.996	66.847	73.047	66.094
80.938	67.493	80.477	69.046	73.136	66.485
78.364	69.031	81.362	67.496	72.264	65.174
78.912	71.915	80.746	68.126	72.528	67.612
78.769	69.898	79.409	67.953	72.217	66.886
79.849	70.820	80.725	67.039	72.396	66.627
78.958	70.655	80.854	67.926	72.497	67.087
78.480	71.382	82.157	67.787	72.660	66.725
79.200	70.072	80.176	66.337	72.926	66.300
79.361	70.987	79.565	68.383	73.066	67.342
79.467	73.089	82.606	66.735	73.513	68.269
76.876	69.426	80.664	67.939	73.618	66.888
80.177	72.337	81.015	69.164	72.938	69.174
80.049	69.782	81.104	67.734	72.283	66.599
81.399	71.454	79.331	67.486	72.807	66.716
78.956	72.448	81.919	68.510	72.826	67.274
77.109	70.184	82.300	66.756	73.193	65.736
79.977	69.648	79.560	67.919	73.458	66.613
78.512	67.946	81.534	67.662	72.686	66.068
77.099	68.220	80.564	68.839	71.900	66.886
78.997	71.221	82.061	67.442	73.288	66.300
79.332	71.076	80.701	69.087	72.412	66.164
79.755	70.982	80.003	67.298	72.743	66.811
79.437	69.727	80.582	66.542	72.944	67.328
81.955	73.219	80.794	68.567	73.159	65.542
80.988	69.309	80.097	67.121	73.278	65.700
80.004	71.467	82.055	66.872	72.544	66.813
78.080	68.753	81.570	67.810	72.196	66.925
79.010	71.350	83.202	68.241	72.830	67.640
79.678	69.288	79.690	67.806	73.299	66.768
78.567	70.465	81.388	67.389	72.503	65.733
77.501	69.800	81.136	66.367	71.422	67.156
81.567	70.272	80.334	67.726	72.665	67.352

79.324	70.450	80.968	67.829	72.200	67.610
79.288	71.940	81.005	68.027	72.128	67.086
81.788	70.564	82.581	66.764	72.361	66.250

3 QC Agents

Batch Efficient TTC (hrs)	Batch Decentralized TTC (hrs)	Batch Centralized TTC (hrs)	One-by-one Efficient TTC (hrs)	One-by-one Decentralized TTC (hrs)	One-by-on Centralized TTC (hrs)
79.804	81.837	71.005	67.640	67.603	66.926
78.345	81.045	68.906	65.989	68.936	66.859
78.974	82.357	69.808	65.785	67.926	66.551
81.171	79.492	71.182	67.243	67.014	67.575
80.041	80.123	71.300	67.049	68.053	66.246
78.200	81.520	70.978	66.977	67.144	66.829
79.479	81.691	70.809	65.980	67.054	67.056
80.533	82.956	72.436	68.622	67.375	67.263
79.297	82.441	71.683	66.636	67.680	66.182
81.438	81.373	73.009	66.773	66.936	66.768
78.467	82.504	71.797	68.204	66.698	67.495
78.143	81.432	71.977	66.782	66.011	66.444
79.099	82.067	70.477	67.535	67.732	67.104
81.587	82.473	71.511	67.247	66.385	66.312
79.267	82.284	71.499	66.044	67.718	66.836
79.074	80.631	70.023	67.081	67.115	67.055
78.635	81.897	71.579	67.733	67.979	67.207
76.567	80.612	70.890	67.457	66.740	67.075
78.303	82.628	71.125	67.971	68.724	65.640
80.414	81.374	71.545	67.083	68.479	66.175
79.627	81.045	70.558	65.427	66.015	66.736
79.867	81.008	71.097	66.577	66.014	68.505
80.229	79.022	72.188	67.189	68.566	65.754
79.464	79.806	70.105	67.660	67.322	66.158
77.100	80.596	70.466	67.502	67.387	66.542
79.398	81.738	72.458	66.544	67.359	66.862
78.800	83.192	69.453	66.938	67.180	68.936
78.779	80.076	69.934	66.183	67.195	66.181
79.094	81.139	71.165	66.755	66.955	67.145
79.873	81.609	70.204	67.170	66.239	67.244
79.328	82.281	71.336	68.207	67.331	67.672

79.355	79.077	69.792	66.581	66.902	65.608
80.469	81.716	68.810	67.079	66.378	66.573
79.030	80.940	69.995	67.391	66.563	65.632
77.761	80.814	68.974	66.827	67.893	67.041
81.130	81.145	71.288	67.056	66.864	68.660
79.303	79.240	70.197	67.230	65.226	67.289
79.662	81.503	70.168	66.771	67.517	66.862
78.320	79.293	71.399	66.523	66.934	68.411
79.654	81.997	70.031	66.981	67.710	65.313
78.827	81.792	72.632	67.832	66.925	67.518
79.448	82.426	72.036	66.791	67.685	67.225
79.073	80.241	70.547	67.554	66.937	67.211
80.687	82.881	68.938	67.182	68.623	68.006
80.363	80.851	72.172	65.644	66.423	66.915
80.773	82.090	69.753	65.620	66.568	66.880
78.082	79.097	71.566	66.801	66.576	68.285
78.229	81.741	71.657	68.444	67.747	67.355
79.037	81.037	70.566	68.215	66.700	67.738
79.062	81.026	71.226	67.592	66.548	66.538
80.283	80.221	69.782	67.445	67.143	68.171
79.213	80.488	71.286	66.886	67.559	68.241
79.650	81.212	70.181	66.490	67.392	66.956
79.977	81.829	69.145	66.390	67.327	66.307
79.712	81.299	71.189	67.012	66.288	66.429
80.171	79.246	71.211	66.754	67.682	65.572
76.375	80.874	70.548	66.799	67.850	65.821
77.340	79.968	69.462	66.077	66.471	66.421
80.337	79.987	70.529	65.883	68.235	66.764
78.933	83.042	69.378	66.498	66.328	66.669
79.148	80.701	70.038	66.583	66.151	66.187
78.119	81.335	70.159	66.608	65.503	68.041
79.650	81.369	71.021	67.130	67.273	67.900
79.425	80.821	68.087	66.510	67.433	65.483
80.781	80.305	70.098	66.002	67.637	66.950
77.814	81.580	70.415	67.822	66.599	66.731
77.952	80.732	69.303	66.591	66.968	67.358
79.343	79.690	69.919	67.627	65.845	66.529
78.761	80.441	70.018	66.806	68.793	67.641
79.769	81.891	71.511	66.464	65.957	68.152

80.486	82.990	69.253	67.091	66.997	66.900
80.291	82.221	70.409	67.914	66.231	67.291
77.796	81.219	68.640	67.287	67.716	68.078
81.569	80.715	70.344	67.868	67.168	68.760
80.410	81.818	72.240	67.779	65.932	67.503
78.001	81.055	70.875	66.942	66.390	67.110
81.611	83.137	72.869	67.361	68.810	66.257
78.427	80.720	69.533	68.022	67.597	66.281
80.404	82.030	71.369	67.900	68.504	66.497
80.235	80.316	72.668	65.954	67.621	67.060
77.523	80.741	70.410	66.238	68.105	66.036
78.741	80.670	69.990	68.760	67.170	65.865
79.450	79.648	69.391	65.788	68.450	66.234
79.443	80.270	71.071	66.273	67.084	67.378
79.508	80.487	71.102	67.510	68.037	66.624
78.252	81.625	70.158	65.039	65.794	65.185
81.009	79.545	71.459	66.483	65.458	66.528
79.416	81.812	73.994	66.490	67.316	66.454
81.396	79.796	72.699	66.634	65.701	66.108
79.448	81.367	70.526	68.139	68.057	68.687
79.349	82.064	70.522	66.389	66.902	68.467
79.527	82.344	70.392	66.238	67.258	67.350
81.240	79.807	69.341	66.002	67.267	68.705
80.534	82.750	69.211	65.864	65.967	66.444
79.372	81.712	69.705	66.597	67.665	66.063
79.677	81.547	70.239	66.872	66.637	66.418
79.454	79.367	70.486	68.096	67.112	67.067
79.536	80.195	72.767	67.990	66.692	68.541
79.286	79.629	68.861	66.781	66.107	66.690
80.181	81.643	72.214	65.589	67.252	67.778

4 QC Agents

Batch Efficient TTC (hrs)	Batch Decentralized TTC (hrs)	Batch Centralized TTC (hrs)	One-by-one Efficient TTC (hrs)	One-by-one Decentralized TTC (hrs)	One-by-on Centralized TTC (hrs)
79.877	71.044	80.813	67.225	66.577	66.756
78.987	71.319	78.792	67.941	67.004	65.971
79.468	70.065	80.312	66.873	65.702	68.047
78.865	72.496	80.760	67.850	66.959	66.764

78.914	70.453	78.762	65.392	67.325	66.457
79.850	71.074	79.430	67.855	67.949	67.945
80.982	73.065	81.962	65.856	66.708	66.509
78.421	72.153	81.812	65.551	67.334	67.519
78.802	72.130	79.472	67.032	66.756	67.297
78.993	72.355	79.643	67.149	66.697	66.715
78.660	70.042	79.476	68.504	66.645	68.108
78.885	70.830	80.402	68.118	66.447	67.010
78.871	70.907	81.030	68.665	67.133	67.567
79.484	69.686	80.755	66.620	67.736	69.442
78.752	72.184	81.038	66.086	67.795	68.374
79.633	69.951	80.186	66.733	67.129	66.986
79.957	71.621	81.760	66.652	68.605	68.298
78.572	71.604	83.035	66.212	66.005	66.811
79.798	70.824	80.241	67.460	66.208	67.494
79.032	70.476	80.444	66.827	66.806	67.923
79.305	70.510	79.444	66.205	66.336	66.476
78.817	70.342	81.844	66.416	67.056	66.364
79.601	70.258	79.170	65.980	66.948	66.574
79.366	70.828	80.122	69.580	66.516	65.955
79.603	70.598	81.526	67.884	67.474	66.471
78.799	70.414	79.914	65.957	67.247	68.343
80.258	69.286	81.317	68.495	67.001	67.485
78.587	71.143	81.493	67.352	66.335	66.908
79.687	69.931	80.894	66.628	69.027	67.741
78.634	69.606	81.995	66.556	67.123	67.798
79.399	69.871	81.326	67.256	67.969	66.614
80.729	68.340	81.484	66.857	66.660	65.331
80.418	69.342	80.980	66.742	67.491	66.107
80.989	70.625	80.003	67.460	67.461	66.432
78.701	70.278	79.760	66.092	67.774	66.230
80.834	70.213	81.492	67.846	68.875	67.648
80.729	69.984	79.956	67.372	66.127	66.094
79.978	71.149	80.617	67.405	70.708	67.835
79.642	71.895	82.278	67.205	67.634	66.154
78.939	69.846	82.308	68.516	66.710	67.475
77.812	70.359	80.197	66.057	66.753	67.260
80.667	71.708	82.259	65.663	65.290	65.268
77.665	73.106	81.091	67.781	67.387	66.625

79.278	72.468	82.098	69.019	66.453	67.799
79.263	69.002	80.003	66.828	65.544	65.800
80.006	70.294	81.003	68.097	67.353	68.014
79.194	70.708	80.339	66.904	66.234	67.713
79.389	72.132	79.998	67.155	65.508	67.968
79.951	70.363	81.944	66.514	67.451	66.396
80.440	70.532	80.706	66.732	67.355	66.994
78.631	68.742	81.100	66.612	67.070	66.302
79.813	70.633	79.539	65.446	67.220	66.865
79.024	71.194	80.808	67.019	66.342	69.243
78.344	71.966	80.627	67.563	67.499	66.926
80.998	71.927	82.163	66.398	65.582	67.672
78.588	71.168	80.147	65.966	67.166	67.292
80.554	71.784	81.433	66.659	67.599	66.685
81.684	68.919	80.833	67.770	66.689	67.115
78.385	71.170	80.119	67.615	68.199	67.588
81.047	70.640	81.519	69.262	68.165	69.980
81.077	68.523	81.374	66.317	67.025	68.180
79.984	71.052	80.607	66.411	67.829	67.256
81.773	69.280	80.619	65.993	67.857	66.601
79.712	71.614	80.511	68.115	65.534	66.712
78.180	72.292	80.304	65.991	66.667	65.879
79.533	69.567	80.651	68.046	66.327	66.853
80.560	70.680	81.271	67.368	66.813	66.905
80.297	71.146	80.493	67.759	65.262	66.967
79.293	70.446	81.476	66.528	65.668	66.946
81.159	70.092	82.584	67.592	66.365	66.428
80.066	71.475	81.773	67.844	68.266	66.815
80.008	70.699	82.547	68.163	67.528	65.961
77.656	72.015	80.888	66.491	67.292	66.960
77.920	71.933	82.016	66.395	66.415	66.900
81.806	70.655	83.172	67.867	65.774	67.245
78.678	70.367	81.114	67.662	67.476	66.581
79.870	71.264	81.280	66.685	67.184	67.508
80.235	72.417	81.397	67.625	68.891	66.440
78.178	71.756	81.650	65.629	67.401	66.419
80.279	69.574	81.403	66.401	66.896	67.962
79.354	71.750	81.073	65.852	65.657	67.388
80.004	72.490	81.789	66.989	66.215	65.796

79.297	71.462	81.435	66.984	67.017	66.173
76.744	70.522	82.164	66.597	67.199	66.306
78.541	69.707	80.601	67.287	69.465	65.704
78.536	69.483	81.768	66.266	67.772	66.025
79.902	70.250	79.704	66.500	66.813	67.291
80.044	71.733	80.864	67.324	66.596	67.197
78.992	70.774	82.173	67.250	66.167	67.596
76.539	69.974	79.094	67.511	67.694	67.585
79.916	68.935	81.241	65.514	65.422	66.680
79.819	70.472	83.488	65.953	65.791	66.343
79.238	72.961	81.765	67.313	67.487	66.385
80.019	70.417	81.166	66.060	66.091	67.003
79.895	68.685	80.942	67.009	67.325	68.562
78.897	72.831	79.953	66.943	68.930	67.617
78.272	69.792	78.587	67.902	66.985	66.517
79.620	71.018	82.439	65.786	68.556	66.780
78.721	71.006	82.288	66.795	67.570	66.742
78.054	70.420	82.904	67.620	67.350	66.173

B.4 Total Recovery Cost Results

2 QC Agents

Batch Efficient TC ($)	Batch Decentralized TC ($)	Batch Centralized TC ($)	One-by-one Efficient TC ($)	One-by-one Decentralized TC ($)	One-by-on Centralized TC ($)
1521	1616	5364	1652	1533	4951
1544	1772	5188	1462	1354	5634
1888	1494	5451	1648	1866	5280
1812	1835	5150	1585	1654	5097
1708	1648	5769	1613	1173	4877
1915	1926	5659	1426	1621	5352
2000	1591	6205	1733	1449	4945
1843	1699	5550	1509	1448	5033
1500	1813	5854	1345	1236	5132
1676	1756	5549	1752	1729	4766
1843	1791	5571	1641	965	4606
1930	1453	6027	1764	1421	5403

1624	1683	5624	1512	1466	5010
1722	1427	5546	1392	1612	4961
1743	1677	5424	1941	1492	5046
1808	1486	5889	1751	1488	4872
1595	1739	5151	1609	1682	4419
1579	1396	5613	1448	1426	4954
1789	1579	5570	1443	1604	4743
1875	1562	5529	1837	1440	5359
1638	1869	5710	1668	1583	4783
1982	1906	5605	1634	1342	4773
1598	1457	5488	1763	1860	5284
1674	1751	5370	1642	1466	5555
1574	1692	5785	1641	1375	4888
1766	2135	5717	1460	1545	5341
1968	1700	5628	1904	1639	5263
1693	1786	5272	1481	1645	5447
1677	1671	5611	1615	1559	4885
1711	1647	5328	1724	1716	5405
2029	1722	5559	1662	1771	5183
1509	1721	5028	1346	1528	4965
1790	1623	5527	1736	1689	4984
1883	1960	5146	1893	1706	5119
1843	1598	5250	1810	1798	5073
1886	1814	5396	1866	1504	5287
1487	1503	5770	1703	1507	4806
1943	1738	5512	2183	1449	5444
2124	1723	5791	1858	1639	5101
1794	1823	5536	1734	1538	5125
1756	1562	5550	1637	1611	5204
2086	1948	5755	1632	1621	5123
1864	1645	5809	1614	1613	5060
1875	1782	5673	1587	1725	5287
1529	1690	5776	1615	1343	4919
1754	1798	5773	1694	1461	4984
1774	1990	5515	1645	1698	5303
1588	1463	5494	1557	1802	5259
1591	2104	5039	2012	1654	4864
1682	1637	5491	1754	1457	5028
1578	1447	5432	1739	1397	5138

1829	1840	5546	1674	1692	4717
1611	1771	5570	1554	1449	5558
1864	1718	5757	1763	1767	5416
1714	1442	5701	1418	1662	4942
1872	1909	5031	1566	1385	4966
1789	1386	5250	1588	1514	4708
1769	1621	5579	1591	1656	4904
1863	1472	5453	1691	1504	5049
1471	1821	5571	1410	1628	5562
1758	1932	5678	1511	1610	5224
1863	1697	5445	1628	1727	4954
2016	1503	5805	1528	1750	5350
1557	1870	5244	1785	1592	4819
1909	1689	5496	1693	1630	5818
1816	1904	5250	1637	1788	4501
1967	1728	5819	1446	1515	4853
1509	1580	5408	1714	1456	5206
2101	1975	5575	1755	1453	5493
1885	1787	5423	1309	1756	4715
1855	1730	5861	1603	1736	5418
1878	2024	5670	1599	1634	5196
2211	1572	5871	1640	1569	4697
2042	1946	5340	1418	1547	4802
1682	1789	5446	1868	1508	4463
1730	1584	5660	1604	1635	5179
1703	1827	5537	1777	1678	5066
1975	1815	5387	1519	1524	5268
1858	1691	5333	1511	1652	4873
1579	1776	5434	1398	1554	4729
1537	1499	4922	1818	1603	4908
1716	1577	5693	1669	1505	5069
1699	1552	5884	1549	1527	4787
1641	1979	5607	1616	1881	4834
1691	1594	5426	1556	1560	4880
1785	1718	5421	1484	1448	4984
1992	1671	5558	1527	1750	4896
1939	1832	5787	1672	1547	5365
1698	1488	5521	1677	1646	4690
1654	1680	5941	1813	1434	4679

1412	1641	5790	1930	1780	5255
1486	1626	5236	1476	1373	4578
1610	1796	5508	1702	1524	4955
1589	1564	5604	1776	1548	4752
1934	1616	5967	1440	1640	4965
1786	1824	5662	1569	1485	5058
2042	1440	6031	1720	1659	4653
1620	1735	5516	1724	1237	5105
1764	1696	5382	1543	1390	5141
1659	1838	4745	1622	1520	4888

3 QC Agents

Batch Efficient TC ($)	Batch Decentralized TC ($)	Batch Centralized TC ($)	One-by-one Efficient TC ($)	One-by-one Decentralized TC ($)	One-by-on Centralized TC ($)
1963	1365	5364	1632	1411	4734
1739	1783	5188	1672	1479	4742
1845	1588	5451	1329	1405	5169
1895	1870	5150	1578	1510	5244
1585	1541	5769	1581	1436	5062
1835	1857	5659	1741	1481	5150
1874	1934	6205	1694	1422	5047
1844	1635	5550	1342	1330	5339
1970	1776	5854	1800	1614	4886
1653	1819	5549	1650	1453	5337
2076	1634	5571	1541	1382	5432
1821	1618	6027	1611	1540	5303
2008	1817	5624	1646	1475	5270
1783	1475	5546	1557	1376	4982
1885	1585	5424	1494	1318	4944
2069	1789	5889	1645	1600	4916
1736	1783	5151	1769	1671	4989
1648	1535	5613	1235	1471	4701
1823	1570	5570	1848	1574	4840
1748	1700	5529	1798	1732	4991
1890	1560	5710	1612	1420	5215
1494	1759	5605	1734	1199	5025
1539	1560	5488	1352	1523	4878
1486	1558	5370	1522	1593	5317

1829	1668	5785	1562	1457	4850
1720	1671	5717	1541	1671	5359
1811	1707	5628	1625	1767	4947
1638	1391	5272	1683	1646	5229
1933	1543	5611	1749	1281	5257
1871	1603	5328	1618	1572	5112
1999	1445	5559	1632	1854	5015
1734	1753	5028	1514	1357	4554
1637	1585	5527	1719	1288	4791
1933	1768	5146	1654	1837	5470
1676	1741	5250	1836	1436	5048
1886	1799	5396	1704	1570	5718
1946	1771	5770	2150	1424	4672
1610	1461	5512	1593	1475	4689
1687	1326	5791	1823	1537	5291
2173	1761	5536	2104	1579	5384
1602	1870	5550	1695	1359	5566
1973	1819	5755	1731	1820	5198
1697	1883	5809	2006	1684	5034
1840	1556	5673	1629	1306	4700
1687	1717	5776	1567	1694	5097
1760	1501	5773	1782	1885	4973
1532	1494	5515	1410	1678	5255
1550	1824	5494	1696	1442	4818
1588	1974	5039	1489	1592	5073
1636	1840	5491	1574	1485	5136
1649	1703	5432	1747	1517	5316
1850	1619	5546	1711	1790	5440
1750	1680	5570	1698	1365	5153
1882	1762	5757	1756	1422	5305
1822	1788	5701	1853	1498	5471
1744	1331	5031	1579	1468	5101
1405	1656	5250	1719	1499	4971
1795	1597	5579	1682	1668	5285
1641	1607	5453	1634	1410	4921
2255	1629	5571	1928	1385	5198
2049	1857	5678	1767	1740	5149
1592	1528	5445	1599	1488	5002
1691	1635	5805	1804	1502	5113

1957	1749	5244	1690	1442	4895
1612	1437	5496	1755	1327	4572
1892	1791	5250	1646	1502	5118
2016	1424	5819	1610	1603	4530
2147	1741	5408	1569	1455	5341
1902	1797	5575	2134	1484	5472
1784	1863	5423	1797	1654	5251
1496	1658	5861	1602	1621	4827
1968	1753	5670	1786	1679	5517
2114	1766	5871	1879	1756	5000
1659	1646	5340	1710	1555	5312
1683	1639	5446	1526	1683	4978
1733	1524	5660	1347	1543	4872
1783	1639	5537	1503	1853	5399
1654	1666	5387	1279	1498	5076
1803	1761	5333	1555	1344	5462
1755	1428	5434	1521	1521	4952
1539	1494	4922	1808	1354	5357
1661	1505	5693	1952	1346	4891
1648	1573	5884	1534	1302	4817
2112	1470	5607	1503	1675	4819
1439	1267	5426	1613	1824	4781
1506	1592	5421	1548	1497	5040
2057	1526	5558	1552	1796	4921
1755	1898	5787	1770	1555	5458
1578	1682	5521	1888	1678	5024
1806	1544	5941	1485	1513	4732
1879	1687	5790	1721	1596	5084
1594	1697	5236	1534	1646	4666
1750	1821	5508	1768	1654	5088
1661	1537	5604	1647	1454	5232
1976	1654	5967	1752	1754	5366
1537	2024	5662	1456	1620	5592
1814	1731	6031	1678	1476	5279
1584	1297	5516	1672	1352	4827
2177	1851	5382	1637	1762	5339
2186	1617	4745	1844	1660	5513

4 QC Agents

Batch Efficient TC ($)	Batch Decentralized TC ($)	Batch Centralized TC ($)	One-by-one Efficient TC ($)	One-by-one Decentralized TC ($)	One-by-on Centralized TC ($)
1728	1792	5532	1510	1323	5186
1867	1643	6146	1459	1447	4805
1760	1563	5710	1597	1722	4705
1754	1631	5797	1823	1572	5135
1405	1526	5465	1761	1286	4974
2097	1458	5359	1619	1385	4726
1870	1553	5534	1632	1572	4855
1904	1610	5418	1509	1565	5200
1864	1164	5807	1594	1558	4970
1876	1703	5624	1630	1644	4861
1436	1792	5838	1746	1507	4787
2029	1666	5641	1617	1607	5163
1725	1738	5731	1757	1704	4992
1487	1653	5316	1654	1486	5047
1584	1609	5498	1794	1481	4840
1937	2064	5256	1547	1251	5274
1801	1633	5640	1569	1387	4812
1705	1697	5818	1697	1696	4824
1646	1395	5244	1820	1698	5259
1745	1608	5719	1645	1367	4946
1598	1859	5396	1748	1848	4882
1684	1577	5134	1629	1268	4928
2023	1647	5691	1805	1542	5326
1675	1787	5815	1561	1559	5437
1721	1710	5912	1608	1729	5123
1504	1600	5662	1594	1261	5125
1879	1681	5830	1791	1603	5558
1521	1614	5485	1724	1554	5113
1912	1926	5791	1455	1398	4899
1534	1431	5367	1762	1523	5443
1708	1996	5355	1955	1760	4791
1611	2064	5050	1952	1429	4998
1851	1628	5486	1529	1645	4977
1709	1888	5276	1605	1602	5477
1519	1606	5304	1541	1669	4967
1902	2035	5762	1621	1678	5536

1623	1744	5608	1763	1468	5014
1747	1828	5549	1759	1675	5309
2023	1626	5889	1765	1575	5024
1881	1461	5290	1625	1530	5149
1721	1602	5333	1942	1570	5438
2072	1535	5745	2160	1553	4978
1766	1589	5783	1684	1631	5277
1448	1770	5637	1743	1687	4908
1997	1517	5776	1741	1580	4847
1659	1693	5114	1783	1975	4782
1736	1877	5216	1811	1405	5156
1600	1683	5766	1599	1685	5251
1649	1707	5332	1207	1711	4825
1706	1776	5424	1540	1441	5317
1760	1837	5575	1557	1636	5006
1942	1822	5723	1577	1705	5223
1760	1748	5581	1673	1825	4452
1888	1715	5117	1577	1516	4743
1692	1628	5735	1490	1699	5303
1885	1749	5679	1656	1565	5158
1932	1775	5615	1508	1659	5383
2182	1756	5675	1705	1438	5185
1995	1822	5604	1358	1706	4728
1867	1695	5463	1697	1586	5026
1921	1656	5074	1935	1585	5266
1768	1760	5241	1685	1577	4891
1766	1469	5131	1776	1775	4877
1759	1620	5568	1406	1561	4933
1667	1569	5848	1569	1609	5572
1962	1612	6026	1413	1488	4845
1862	1603	5209	1548	1909	5625
1907	1852	5600	1425	1454	5073
1774	1822	5514	2085	1368	5074
1974	1744	5727	1776	1472	5238
1875	1745	5414	1588	1416	5029
1748	1688	5491	1685	1585	4801
1697	1804	6154	1854	1859	5184
1907	1780	5432	1700	1689	5507
1726	1724	5584	1694	1677	5467

1664	1522	5740	2078	1572	5263
1572	1786	5086	1661	1646	5279
1886	1820	5951	1560	1828	4951
1649	1502	6425	1646	1778	4607
1705	1346	5736	1765	1388	5824
1567	1595	5508	1704	1272	4974
1728	1598	5540	1645	1513	5632
1716	1829	5258	1576	1495	5008
2020	1682	5441	1572	1758	5350
1827	1546	5485	1558	1440	4752
1506	1802	5588	1619	1364	4942
2352	1753	5686	1655	1656	5228
1940	1788	5427	1530	1534	5150
1482	1753	5055	1678	1522	5299
1803	1679	4990	1672	1400	5035
1532	1587	5871	1619	1529	4982
1611	1736	5076	1427	1483	4681
1715	1535	5873	1783	1684	4838
1642	1626	5445	1453	1727	4932
1793	1722	5522	1607	1591	5310
1850	1727	5322	1638	1524	5073
1952	1659	5527	1840	1868	4750
1696	1660	5597	1788	1681	5002
1852	2169	5840	1647	1533	4722
1518	1573	5379	1319	1555	5139