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Robust Control for Single Unit Resource Allocation Systems

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1. Introduction

Supervisory control for deadlock-free resource allocation has been an active area of manufacturing systems research. Most work, however, assumes that allocated resources do not fail. Little research has addressed allocating resources that may fail. Automated manufacturing systems have many types of components that may fail unexpectedly. We develop robust controllers for single unit resource allocation systems with unreliable resources (Chew et al., 2008; Chew et al., 2011; Chew & Lawley, 2006; Lawley, 2002; Lawley & Sulistyono, 2002; Wang et al., 2008; Wang et al., 2009). These controllers guarantee that when unreliable resources fail, parts requiring failed resources do not block the production of parts not requiring failed resources. Further, while resources are down, the system is controlled so that when repair events occur, the system is in a safe and admissible state. There is little manufacturing research literature on robust supervision. Reveliotis (1999) considers the case where parts requiring a failed resource can be re-routed or removed from the system through human intervention. Park & Lim (1999) address existence questions for robust supervisors. Hsieh (2004) develops methods that determine the feasibility of production given a set of resource failures modelled as the extraction of tokens from a Petri net. In contrast, our work models the failure of the workstation server while assuming that buffer space remains accessible after the failure event. We assume that when the server of a workstation fails, we can continue allocating its buffer space up to capacity, but that none of the waiting parts can be processed and thus cannot proceed along their routes until the server is repaired. We further assume that server failure does not prevent finished parts occupying the workstation’s buffer space from being moved away from the workstation and proceeding along their routes. Finally, we assume that server failure does not damage or destroy the part being processed and that failure can only occur when the server is working. The last two assumptions are made for notational efficiency and presentation clarity. They can be easily relaxed by adding appropriate events and state variables to our treatment. Our objective is to control the system so that failure of an unreliable resource does not prevent processing of parts not requiring the failed resource. When a resource fails, all parts in the system requiring the failed resource for future processing are unable to complete until the failed resource is repaired. Because these parts occupy buffer space, they can block production of parts not requiring the failed resource. Thus, we want to assure that, when unreliable resources fail, the buffer space allocation can evolve under normal operation so
that parts not requiring failed resources can continue production. Operation must continue to obey part routings and must assure that when a failed resource is repaired, the system is not in an unsafe state. We refer to supervisors guaranteeing this as robust.

The remainder of the chapter comprises the following sections. Most briefly, Section 2 discusses the way we model our systems. An example system is presented in this section to motivate properties that robust controllers must possess. In Section 3, we develop robust controllers for systems with multiple unreliable resources where each part type requires at most one unreliable resource. Specifically, Subsection 3.1 develops two robust controllers using a neighbourhood policy, a modified version of banker’s algorithm, and a single step look ahead policy. Subsection 3.2 uses a resource order policy to construct another robust controller; Subsection 3.3 employs a notion of shared buffer capacity to develop a robust controller. Relaxing the restriction, Section 4 builds robust controllers for systems for which part types may require multiple unreliable resources. Finally, Section 5 concludes the chapter and discusses future research directions.

2. Modelling of robust control

There are two subsections in this section. Specifically, we will discuss the way we model our systems in Subsection 2.1. Subsection 2.2 will provide examples to motivate properties that robust controllers must possess.

2.1 The discrete event system

We model our systems using the approach of Ramadge & Wonham (1987). This is necessary to define the properties that we want our supervisors to enforce. The following model is similar to that developed by Lawley & Sulistyono (2002), but differs in that now we have more complex failure scenarios and thus some of the underlying formalism has to be generalized. Figure 1 provides an example for the following development.

The system is defined as a 9–tuple vector \( S = (R, C, P, \rho, Q, \Omega, \Sigma, \xi, \delta) \). In S, \( R \) is the set of system resource types, with \( R = R^R \cup R^U \), \( R^R \cap R^U = \emptyset \), where \( R^R \) is the set of reliable resource types, not subject to failure and \( R^U \) is the set of unreliable resource types, subject to failure. Let \( C = \{ C_i : i = 1 \ldots |R| \} \) where \( C_i \) is the capacity of the buffer space associated with system resource type \( r_i \in R \).

The set \( P \) of part types is produced by the system with each part type \( P_j \in P \) representing an ordered set of processing stages, \( P_j = (P_{j|1} \ldots P_{j|\Omega}) \), where \( P_{jk} \) represents the \( k \)th processing stage of \( P_j \). Also, let \( R(P_{jk}) = (P_{jk} \ldots P_{j|\Omega}) \) be the residual part stages. We will use \( p_{jk} \) to represent a part instance of \( P_{jk} \). Let \( \rho(P_{jk}) \rightarrow R \) such that \( \rho(P_{jk}) \) returns the resource type required by \( P_{jk} \). Thus, the route of \( P_j \) is \( T_i = (\rho(P_{j1}) \ldots \rho(P_{j|\Omega})) \), and the residual route \( RT_i = (\rho(P_{j\Omega}) \ldots \rho(P_{j|\Omega})) \). Finally, let \( \Omega = \{ P_{jk} : \rho(P_{jk}) = r_i \in R \} \), the set of part type stages associated with resource \( r_i \in R \).

We will suppose that our resource types are workstations with buffer space for staging and storing parts and a processor or server for operating on parts. We will use the standard assumption from queuing theory that the server is not idle so long as there are unfinished parts in a workstation’s buffer space. The resource units that we are concerned with allocating are instances of the workstation’s buffer space. The controllers that we design are not intended to allocate the server among parts waiting at the workstation. We assume this to be done by some local queuing discipline.

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Fig. 1. An example system with two unreliable resources

Workstation failure will imply the failure of the workstation’s server, not any of its buffer space. We will assume that when the server of a workstation fails, we can continue to allocate its buffer space up to capacity, but that none of the waiting parts can be processed and thus cannot proceed along their respective routes until the server is repaired. We further assume that server failure does not prevent finished parts occupying the workstation’s buffer space from being moved away from the workstation and proceeding along their respective routes. Finally, we assume that server failure does not damage or destroy the part being processed and that failure can only occur when the server is working.

We are now in a position to define the system states and events. Let Q represent the set of system states, where $Q = \{q_{i} \in Q_{i} | i=1...|R| \}$, with $q_{i}$ being the status of the server of workstation i (0 if failed, 1 if operational), $y_{b}$ being the number of unfinished units of $P_{b}$ (parts waiting or in-process) located in the buffer space of $\rho(P_{b})$, and $x_{k}$ being the number of finished units of $P_{b}$ located in the buffer space of $\rho(P_{b})$. $Q_{i}$ is the set of initial states with $q_{i} \in Q_{i}$ being the state in which no resources are allocated and all servers are operational. The dimension of q is $\sum_{j=1}^{i} 2|P| + |R|, i$.

Let $\Sigma = \Sigma_{\rho} \cup \Sigma_{w}$ where $\Sigma_{\rho} = \{\alpha_{k} : j=1...|P| \}$ and $k=1...|P| + 1$ is the set of controllable events with $\alpha_{k}$ representing the allocation of $\rho(P_{b})$ to a part instance of $P_{b}$; that is, $\alpha_{k}$ is the event that a part instance of a part type $P_{b}$ advances into the buffer space of a workstation that will perform its $k^{th}$ operation. Then, $\alpha_{k} |P| + 1$ represents a finished part of type $P_{b}$ leaving the system. We assume that the supervisor controls the occurrences of these events through resource allocation decisions.

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We have $\Sigma_u=\Sigma_{u1}\cup\Sigma_{u2}$ being the set of uncontrollable events where $\Sigma_{u1}=\{\beta_{jk} : j=1,\ldots,|P_j|\}$ and $k=1,\ldots,|P|$. Then, $\Sigma_u=\{\kappa,\eta : r\in R^U\}$ represents the failure ($\kappa$) and repair ($\eta$) of the server of unreliable resource $r\in R^U$. Service completions, failures and repairs are assumed to be beyond the controller’s influence.

Let $\xi:Q\rightarrow 2^\Omega$ be a function that, for a given state, returns the set of enabled events. This function is defined for a state, $q\in Q$, as follows:

1. For $P_j\in\Omega_0$, if $C_i - \sum_{p\in U_j} (y_{jk} + x_{jk}) > 0$, then $\alpha_j \in \xi(q)$.

   Events that release new parts into the system are enabled when space is available on the first required workstation in the route.

2. For $P_j\in\Omega_0$, if $y_{jk}>0$ and $sv_i=1$, then $\beta_{jk} \in \xi(q)$.

   If a part is at service, then the corresponding service completion event is enabled.

3. For $r\in R^U$, $P_k\in\Omega$ and $\beta_{jk} \in \xi(q) \Rightarrow \kappa_i \in \xi(q)$.

   If the server is busy with a part, then the corresponding failure event is enabled.

4. For $r\in R^U$, if $sv_i = 0$, then $\eta \in \xi(q)$ and $\beta_{jk} \in \xi(q) \forall P_k\in\Omega$.

   If the server is failed, the corresponding repair event is enabled and the corresponding service completion events are disabled.

5. For $P_j\in\Omega_0$ if $1 < k \leq |P_j|$, if $x_{jk} > 0$ and $C_i - \sum_{p\in U_j} (y_{jk} + x_{jk}) > 0$, then $\alpha_{jk} \in \xi(q)$.

   When a part finishes its current operation and buffer space becomes available at the next required workstation in its route, the event corresponding to advancing the part is enabled.

6. For $P_k\in|P|\in\Omega_0$ if $x_{jk} > 0$, then $\alpha_{jk,|P|+1} \in \xi(q)$.

   If a part has finished all of its operations, the event corresponding to unloading it from the system is enabled.

The state transition function is now defined as follows. The transition function, $\delta$, is a partial function from the cross product $Q\times\Sigma$ to the set $Q$ of system states. Specifically, let $\delta:Q\times\Sigma\rightarrow Q$ such that

\[
\delta(q,\alpha_j)=q-e_{jk,1}+e_{jk}\quad \text{advancing a part } p_{j,k-1};
\]

\[
\delta(q,\beta_{jk})=q-e_{jk}+e_{jk}\quad \text{service completion of a part } p_k;
\]

\[
\delta(q,\kappa)=q-e_{\kappa}+e_{\kappa}\quad \text{failure of server } i;
\]

\[
\delta(q,\eta)=q+e_{\eta}\quad \text{repair of server } i;
\]

where $e_{jk,1}, e_{jk}, e_{\kappa}$, and $e_{\eta}$ are the standard unit vectors with components corresponding to $x_{jk,1}$, $y_{jk}$, $x_{jk}$, and $sv_i$ being 1, respectively. Note that, $e_{\kappa,|P|+1} = e_{\eta,0} = 0$, the zero vector with the same dimension, and that $p_0$ represents a raw part of $P$ waiting to be released into the system.

We assume that $|R^U|\geq 1$. In this case, any subset of the unreliable resources can be simultaneously in a failed state. Thus, if one of the $\binom{|R^U|}{i}$ subsets of size $i$, $i=1,\ldots,|R^U|$, is down, we want the remaining resources to continue producing parts not requiring any of the failed resources without human intervention to remove or rearrange the parts requiring failed resources. Further, when one of the failed resources is repaired, we want production of parts requiring that resource to resume. A robust controller must possess certain properties in order to accomplish the above-mentioned characteristics.
2.2 Motivating examples for properties of robust supervisory control

This subsection motivates a set of desired properties for a robust controller based upon an example production system. Figure 1 presents an example manufacturing system with two unreliable resources. The stages, routes, and resource capacities are given, as is the complete discrete event model. This model enumerates the resources, capacities, events, and so forth. For now, we will constrain our discussion to the system states presented in Figures 2-4. We recall that, by definition, a resource allocation state is safe if, starting from that state, there exists a sequence of resource allocations/deallocations that completes all parts and takes the system to the empty and idle state, the state in which no resources are allocated and no servers are busy. Our underlying assumption is that if a resource allocation state is safe, then, under correct supervision and starting from that state, it is possible to produce all part types indefinitely.

We have several control objectives for the system of Figure 1. First, we desire that the controller guarantee deadlock-free operation, i.e., that it keeps the system producing all part types. Second, in the event that \( r_2 \) fails, we want to continue producing part types not requiring \( \{P_3, P_4\} \), without having to intervene by clearing the system of parts requiring \( r_2 \). Similarly, in the event that \( r_9 \) fails, we want to continue producing part types not requiring \( \{P_1, P_2, P_4\} \), again without having to intervene by clearing the system of parts requiring \( r_9 \). Further, if both \( r_2 \) and \( r_9 \) are in the failed state, we want to continue producing part types not requiring \( r_2 \) or \( r_9 \), \( \{P_4\} \), again without explicit intervention.

Consider for example the state given in Figure 2. This state is safe; however, if \( r_2 \) fails while processing part \( p_{27} \) in this state, the production of both \( P_3 \) and \( P_4 \) will be blocked by two \( p_{23} \)'s at \( r_4 \). Note that if we advance a \( p_{23} \) from \( r_4 \) to \( r_6 \), then production of \( P_4 \) can proceed. However, production of \( P_3 \) will now be blocked. Thus, this state does not satisfy our condition that after the failure of \( r_2 \), we should be able to continue producing both \( P_3 \) and \( P_4 \).

As another example, consider the state of Figure 3. Again, we see that this state is safe. However, if \( r_9 \) fails while processing part \( p_{35} \) in this state, production of part types \( P_1 \) and \( P_2 \) will be blocked by \( p_{34} \) at \( r_6 \), although the production of \( P_4 \) is unaffected.

![Fig. 2. An undesirable system state since unreliable resource \( r_2 \) may fail while processing part \( p_{27} \)](https://www.intechopen.com)
Thus, these examples illustrate that parts requiring a failed resource can prevent the system from producing parts not requiring the failed resource through propagation of blocking. Our objective is to develop supervisory controllers that avoid this by guaranteeing that if an unreliable resource fails, it is possible to redistribute the parts requiring that resource so that part types not requiring that resource can continue to produce.

For the third objective, consider the state of Figure 4. Again, we see that the state is safe. If $r_2$ fails, production of $P_3$ is blocked by $p_{11}$ at $r_6$. Further, production of $P_4$ is blocked by $p_{33}$ at $r_5$. We note that by advancing $p_{11}$ from $r_6$ to its next required resource, $r_3$, the blockages of $P_3$ and $P_4$ can now be resolved and thus the system can continue producing both $P_3$ and $P_4$, as desired. However, when $r_2$ is repaired, the system is no longer safe since resources $r_2$ and $r_3$ are now involved in deadlock. This illustrates that our controller must guarantee that any redistribution of parts requiring the failed resource does not result in system deadlock when the resource is repaired.

The above discussion lays a foundation for a robust supervisory controller. In summary, a supervisory controller is said to be robust to resource failures of $R^U$ if the supervisory controller satisfies Property 2.2.

**Property 2.2:**

2.2.1: The supervisory controller ensures continuing production of part types not requiring failed resources, given that additional failures/repairs do not occur.

2.2.2: The supervisory controller allows only those states that serve as feasible initial states if an additional resource failure occurs.

2.2.3: The supervisory controller allows only those states that serve as feasible initial states if a failed resource is repaired and becomes operational.

We say that a state is a *feasible initial state* if, starting from that state, it is possible to produce all part types not requiring failed resources. The formal development and definition of this property using language theory is presented in Chew and Lawley (2006).
3. Robust control for systems with multiple unreliable resources

This section endeavours to delve into robust control for single unit resource allocation systems with unreliable resources.

3.1 Robust control using a neighbourhood policy

This subsection develops controllers that satisfy Property 2.2 above, while maintaining polynomial complexity. Each controller is a conjunction of a modified deadlock avoidance policy and a set of neighbourhood constraints. The deadlock avoidance policy guarantees deadlock-free operation, while the neighbourhood constraints control the distribution of parts that require unreliable resources. Subsection 3.1.1 develops the neighbourhood constraints, NHC. Subsection 3.1.2 constructs a supervisor based on a modified Banker's Algorithm and NHC, while subsection 3.1.3 develops a supervisor based on single-step look-head (SSL) and NHC. The complete proofs can be found in Chew and Lawley (2006).

3.1.1 A neighbourhood policy

In this subsection, we discuss neighbourhood constraints based on the notion of failure dependency. Informally, a resource is failure-dependent if every part that enters its buffer space requires some future processing on an unreliable workstation. Thus, all unreliable resources are failure-dependent. Some reliable resources may also be failure-dependent if they only process parts that require future processing on an unreliable resource. This is defined more precisely later. For each failure-dependent resource, we generate a neighbourhood. The neighbourhood of a failure-dependent resource is a virtual space of finite capacity that is used to control the distribution of parts requiring that failure-dependent resource. Again, this is formalized in the following, where we extend the neighbourhood concepts presented by Lawley & Sulistyono (2002) for systems with multiple unreliable resources. We first discuss and illustrate neighbourhood concepts, and then illustrate how neighbourhood constraints are constructed for failure-dependent resources.
Recall that \( R_U \) is the set of unreliable resources in the system \( S \), and that \( \Omega_{i} = \{ P_{i,k} : p(P_{i,k}) = r_i \in R \} \) is the set of part type stages supported by resource \( r_i \). If \( r_i \in R_U \), then \( r_i \in R \) is said to be failure-dependent on \( r_i \) if \( \forall P_{i,k} \in \Omega_{i}, \exists P_{j,k+\delta} \in \Omega_{j} \) with \( \delta > 0 \). In other words, \( r_i \) is failure-dependent on \( r_i \) if every part that enters the buffer of \( r_i \) requires future processing on unreliable resource \( r_i \) (note that \( r_i \) is failure-dependent on itself). For \( r_i \in R_U \), let \( R^D = \{ r_i : r_i \in R \land \forall P_{i,k} \in \Omega_{i}, \exists P_{j,k+\delta} \in \Omega_{j} \} \) be the set of failure-dependent resources on \( r_i \), and let \( R^{FD} = \bigcup_{r_i \in R_U} R^D \) and \( R^{NF} = R \setminus R^{FD} \).

For each failure-dependent resource of \( R^{FD} \), we construct a neighbourhood. The neighbourhood of \( r_i \in R^{FD} \), \( NH_i \), is defined as the set of part type stages that require \( r_i \) now or later in their processing and have no intervening failure-dependent resources of \( R^{FD} \). Formally, \( NH_i = \Omega_{i} \cup \{ P_{i,k} : \exists \delta > 0 \text{ with } P_{i,k+\delta} \in \Omega_{i} \land \forall d \in [0,\delta), p(P_{i,k+d}) \not\in R^{FD} \} \). Thus, if \( p(P_{i,k+c}) = r_i \in R^{FD} \), then \( p(P_{i,k+c}) \neq r_i \in R^{FD} \), with \( r_i \neq r_{i^'}, \) and \( (p(P_{i,k+c}), p(P_{i,k+c}+1), \ldots, p(P_{i,k+c+n})) \cap R^{FD} = \emptyset \), then \( R^{FD} = \{ P_{i,k+1}, \ldots, P_{i,k+c+n} \} \subseteq NH_i \), and \( P_{i,k+c+n} \not\in NH_i \). Let \( NH_i = \{ NH_i : r_i \in R^{FD} \} \) be the neighbourhood set for \( r_i \in R_U \), and let \( NH_i = \{ NH_i : r_i \in R_U \} \).

For example, the system of Figure 1 has two unreliable resources, \( R_U = \{ r_2, r_3 \} \). Note that anytime \( r_1 \) appears in a route, \( r_2 \) appears later in the route, and thus, \( R^{FD} = \{ r_1, r_2 \} \). Also, anytime \( r_1 \) or \( r_3 \) appear in a route, \( r_3 \) appears later in the route, so, \( R^{FD} = \{ r_1, r_2, r_3 \} \). Thus, \( NH_1 = \{ NH_1, NH_2 \} \) and \( NH_2 = \{ NH_1, NH_3, NH_4 \} \), where the neighbourhoods are as follows:

\[
NH_1 = \{ P_{i,1}, P_{i,2}, P_{i,3}, P_{i,4}, P_{i,5} \},
NH_2 = \{ P_{i,1}, P_{i,2}, P_{i,3}, P_{i,4}, P_{i,5} \},
NH_3 = \{ P_{i,1}, P_{i,2}, P_{i,3}, P_{i,4}, P_{i,5} \},
NH_4 = \{ P_{i,1}, P_{i,2}, P_{i,3}, P_{i,4}, P_{i,5} \}.
\]

To understand this construction, consider \( NH_1 \) and \( NH_2 \). Note that \( \Omega_{i} = \{ P_{i,1}, P_{i,2}, P_{i,3}, P_{i,4}, P_{i,5} \} \) and \( \Omega_{i} = \{ P_{i,1}, P_{i,2}, P_{i,3}, P_{i,4}, P_{i,5} \} \). Since \( \Omega_{i} \subseteq NH_1 \), \( \{ P_{i,1}, P_{i,2}, P_{i,3}, P_{i,4}, P_{i,5} \} \subseteq NH_2 \). Now consider \( T_1 = (P_{i,1}, p(P_{i,2}), p(P_{i,3}), p(P_{i,4}), p(P_{i,5})) = \{ r_1, r_2, r_3, r_4, r_5 \}. \) Since \( \{ r_1, r_2, r_3, r_4, r_5 \} \subseteq NH_2 \). Similarly, \( T_2 = (P_{i,1}, p(P_{i,2}), p(P_{i,3}), p(P_{i,4}), p(P_{i,5})) = \{ r_1, r_2, r_3, r_4, r_5 \} \). Since \( \{ r_1, r_2, r_3, r_4, r_5 \} \subseteq NH_2 \). Thus, we get \( NH_1 = \{ P_{i,1}, P_{i,2}, P_{i,3}, P_{i,4}, P_{i,5} \} \) and \( NH_2 = \{ P_{i,1}, P_{i,2}, P_{i,3}, P_{i,4}, P_{i,5} \} \).

Although all parts supported by \( r_5 \) later need an unreliable resource, \( r_5 \) is shared by \( r_2 \) and \( r_3 \), and thus it is not failure-dependent on either. This implies that failure-dependent sets are disjoint, i.e., \( R^{FD} \cap R^{FD} = \emptyset \). Furthermore, we observe that no part stage is in more than one neighbourhood, i.e., \( NH_1 \cap NH_2 \cap NH_3 \cap NH_4 \cap NH_5 = \emptyset \). These and other important neighbourhood properties are established in Chew and Lawley (2006).

We restrict the number of parts allowed in a neighbourhood. Our intention is to guarantee that every part in the neighbourhood of a failure-dependent resource has capacity reserved at that resource. That is, we want to be able to advance every part requiring an unreliable resource into its associated failure-dependent resource in the event of a resource failure so that it will not block production of parts not requiring the failed resource. In the example, for a permissible state, we want, for example, every part in \( NH_1 = \{ P_{i,1}, P_{i,2}, P_{i,3}, P_{i,4}, P_{i,5} \} \) to have a reserved unit of buffer at \( r_5 \). As a consequence, we will reject a state if this constraint is violated. For instance, a state is not admissible if, at this state, the sum of parts in \( NH_1 > 1 \); recall that \( r_5 \) has a single unit of capacity. To see this, at this inadmissible state, if \( r_5 \) fails, at least one part of \( NH_1 \) must reside at \( r_5 \).

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We now construct neighbourhood constraints to enforce the above intention. The constraint for a neighbourhood, say $NH_i$, is an inequality of the form $Z \leq C$, where $Z = \sum_{p_k \in NH_i} (x_{jk} + y_{jk})$. Recall that $x_{jk}$ is the number of finished instances, and $y_{jk}$ is the number of unfinished instances, of $p_k$ located in the buffer of $\rho(p_k)$; and that the right hand side $C$ is the capacity of $r_i$. $NH_i$ is said to be capacitated if $Z = C$, and over-capacitated if $Z > C$.

Define the set of all possible neighbourhood constraints with respect to $r_i \in \mathbb{R}^d$ as:

$$\text{NHC}^i = \{ Z \leq C, \text{ } NH_i \in NH^i \}.$$  

In the example, we have

$$\text{NHC}^i = \{ Z_1 = \sum_{p_k \in NH_i} (x_{jk} + y_{jk}) \leq C_1, Z_2 = \sum_{p_k \in NH_i} (x_{jk} + y_{jk}) \leq C_2 \}$$

$$\text{NHC}^i = \{ Z_3 = \sum_{p_k \in NH_i} (x_{jk} + y_{jk}) \leq C_3, Z_4 = \sum_{p_k \in NH_i} (x_{jk} + y_{jk}) \leq C_4 \}$$

Constraints of $\text{NHC}^i$ assure that no neighbourhood of $NH^i$ becomes over-capacitated.

As Lawley & Sulistyono (2002) discuss, $\text{NHC}^i$ may induce deadlock among failure-dependent resources of $\mathbb{R}^d$, since if all neighbourhoods are capacitated, parts cannot move from one neighbourhood to another without over-capacitating a neighbourhood. In the example, a state may satisfy both $1= Z_1 \leq C_1=1$ and $1= Z_2 \leq C_2=1$. But, a part moves from one of these associated neighbourhoods to another must over-capacitate the other neighbourhood. To resolve this dilemma, we develop an additional set of constraints, $\text{NHC}^2$.

It is first necessary to compute the set of strongly connected neighbourhoods for $\text{NHC}^1$. To do this, for each $r_i \in \mathbb{R}^d$, we construct a directed graph $(NH^i, A^i)$ where $A^i = \{(NH_i, NH_k) : \exists P_{jk} \in NH_i \cup NH_k \}$. Thus, in operation, there will be part flow from $NH_2$ to $NH_1$. We then compute the set of strong components of $(NH^i, A^i)$ using standard polynomial graph algorithms (Cormen et al., 2002). For example, we see that $NH_1$ and $NH_2$ are strongly connected, since $[P_{1,2}P_{2,3}] \subseteq NH_2$ and $[P_{2,3}P_{1,2}] \subseteq NH_2$. Therefore, in operation, there is flow from $NH_1$ to $NH_2$, and from $NH_2$ to $NH_1$. Let $SC^1$ be the set of strongly connected components of $(NH^1, A^1)$. Then, $SC^2 = \{ SC^1 = [NH_1 \cup NH_2] \}$, and $SC^9 = \{ SC^1 = [NH_1 \cup NH_2], SC^2 = [NH_1 \cup NH_2], SC^3 = [NH_1 \cup NH_2] \}$. Then, $\text{NHC}^2$ is stated as follows:

$$\text{NHC}^2 = \{ Z \leq Z_1 < C_1 + C_2 : [NH_1 \cup NH_2] \subseteq SC^m, m=1... |SC^1| \}.$$  

Hence, for every strongly connected component of $(NH^1, A^1)$, $\text{NHC}^2$ guarantees that at most one neighbourhood can be capacitated at a time. In the example, we have the following:
\[ \text{NHC}_1^3 = \{ Z_1 + Z_2 < C_1 + C_2 \}, \text{NHC}_2 = \emptyset. \]

\[ \text{NHC}_3 \]

 guarantees that \( \text{NHC}_1 \) and \( \text{NHC}_2 \) are not simultaneously capacitated.

To summarize, \( \text{NHC} = \text{NHC}_1 \cup \text{NHC}_2 \) guarantees that no neighbourhood is over capacitated, and that neighbourhoods with mutual flow dependencies are not simultaneously capacitated. The complete set of neighbourhood constraints is defined as:

\[ \text{NHC} = \{ \text{NHC}_i : r_i \in \mathbb{R} \}. \]

Note that in the worst case, we generate one constraint for each pair of resources and thus the size of \( \text{NHC} \) is of \( O(|R|^2) \).

Chew and Lawley (2006) establish several important properties of \( \text{NHC} \). These properties are required to establish robustness of the two supervisors that we develop later. We next modify two deadlock avoidance policies that we use in conjunction with \( \text{NHC} \) to develop robust supervisors.

### 3.1.2 Banker’s algorithm

In this subsection, we configure Banker’s Algorithm (BA) (Habermann, 1969) to work with \( \text{NHC} \). BA is perhaps the most widely known deadlock avoidance policy (DAP), and its underlying concepts have influenced the thinking of numerous researchers. BA is a suboptimal DAP in the sense that it achieves computational tractability by sacrificing some safe states. BA avoids deadlock by allowing an allocation only if the requesting processes can be ordered so that the terminal resource needs for the \( i^{th} \) process, \( P_i \), in the ordering can be met by pooling available resources and those released by completed processes \( P_1, P_2 \ldots P_{i-1} \). The ordering is essentially a sequence in which all processes in the system can complete successfully. BA is of \( O(mn \log n) \) where \( m \) is the number of resource types and \( n \) is the number of requests. Other manufacturing related work also uses BA (Ezpeleta et al., 2002; Lawley et al., 1998; Reveliotis, 2000).

Our modifications are straightforward and are a generalization of those undertaken by Lawley & Sulistyono (2002). Our objective is to search for an ordering of parts that advances failure-dependent parts (those requiring unreliable resources) into the resource of their current neighbourhood, and non-failure-dependent parts (those not requiring unreliable resources) out of the system. Again, the ordering is such that the resources required by the first part are all available, those required by the second part are all available after the first part has finished and released the resources held by the part, and so forth. If the system can be cleared in this way (all failure-dependent parts are advanced into failure-dependent resources and all non-failure-dependent parts are advanced out of the system), then we can guarantee that if any unreliable resource fails, the system can continue producing parts that do not require this failed resource.

In the following, let \( \Lambda = \Lambda^\text{NFD} \cup \Lambda^\text{FD} \) be the set of part type stages instantiated in \( q \) whose parts hold non-failure-dependent resources, where \( \Lambda^\text{NFD} \) is the set of non-failure-dependent part type stages (those that do not require failure-dependent resources in the residual route) and \( \Lambda^\text{FD} \) is the set of failure-dependent part type stages (those that do require failure-dependent resources in the residual route). We now present our modified version of BA as Algorithm A1 as follows.
Algorithm A1:

Query: Is state q admissible?
Input: state q;
Output: ACCEPT / REJECT
Step 1: Initialization
For P(u)
   For r, R
      ALLOCATION[u][v]=0
      AVAILABLE[v]=C_V
   End For
End For
For P(u)=P_k and r = (P_k)
   ALLOCATION[u][v]=x_k+y_k
End For
For P(u)=P_k and r = (P_k)
   For r, R_{F}
      NEED[u][v]=1
   End For
End For
For r, R_{FD}
   NEED[u][v]=1
End For
For r, R_{FD}
   NEED[u][v]=0
End For
For r = (P_k) and r_{i}= (P_{k+1}),
c=k,...,|P_i|
   NEED[u][t]=NEED[u][s]*NEED[u][t]
End For

Step 1 of the algorithm configures the data structures required. For every part type stage represented in the system, these capture the current resource holding and the future processing need. These structures also capture the resource availability of resources in the state being tested. Three additional comments regarding the algorithm are in order. First, the need for every failure-dependent resource is explicitly set to zero, so this version looks only at the availability of non-failure-dependent resources. Second, for non-failure-dependent part type stages (those not requiring unreliable resources), the need for every resource in the residual route (except the one held) is set to one. Finally, for failure-dependent part type stages (those requiring unreliable resources), the need for every resource in the residual route (except the one held) up to the one immediately preceding the first encountered failure-dependent resource is set to one, all others are set to zero. Note that these are the resources such a part will need to advance into the failure-dependent resource of its current neighbourhood. Step 2 then executes the usual Banker’s logic. Algorithm A1 is not correct by itself, since it does not handle allocation of failure-dependent resources (for detailed examples the reader is referred to the work by Lawley & Sulistyono).
(2002)). However, A1 and NHC together form a robust controller, that is, if we allow the system to visit only those states acceptable to both A1 and NHC, then the system operation will satisfy the requirements of Property 2.2. The detailed proofs for this are given in Chew and Lawley (2006). The supervisor is defined as follows:

**Definition 3.1.1**: Supervisor $\Delta_1 = A1 \land NHC$.

Supervisor $\Delta_1$ permits a system state that satisfies both A1 and NHC in runtime. Consider Figure 5, which illustrates a state, say q, in which $r_4$ holds $p_{23}$ and $p_{41}$; and $r_5$ holds $p_{33}$. It is clear, at $q$, that there exists an admissible sequence by A1; that is, $p_{33}$ can advance into failure-dependent resource $r_6$; $p_{23}$ can advance into failure-dependent resource $r_7$; and finally, $p_{41}$ can be advanced out of the system. In addition, $q$ satisfies NHC since

$$
NHC^1 = \{ Z_1 = 1 \leq 1, (\text{there is one } P_{23}) \} \quad Z_2 = 0 \leq 1 ;
$$

$$
NHC^2 = \{ Z_1 = 0 \leq 1, \quad Z_3 = 0 \leq 1, \quad Z_8 = 1 \leq 1 (\text{there is one } P_{33}) \} ;
$$

$$
NHC^3 = \{ 1 + 0 < 1 + 1 = 2 \}; \quad NHC^4 = \emptyset .
$$

Therefore, $q$ is an admissible state by $\Delta_1$. Supervisor $\Delta_1$ will prohibit, at $q$, advancing $p_{23}$ into $r_6$ (where it becomes $p_{24}$) because $p_{24}$ and $p_{33}$ will block, causing the resulting state to violate A1 although not NHC. Loading a $p_{31}$ into $r_7$ at $q$ is also precluded by $\Delta_1$ since the resulting state violates $NHC^3$, although not A1. However, advancing $p_{33}$ one step into $r_5$ or loading a $p_{31}$ into $r_8$ will result in an admissible state.

**Fig. 5. An admissible system state by supervisor $\Delta_1$**

Supervisor $\Delta_1$ is of polynomial complexity since both A1 and NHC require polynomial time for runtime implementation. Chew and Lawley (2006) formally establish that $\Delta_1$ yields a robust supervisor for systems where every part type requires in its route at most one unreliable resource.
A Single step look ahead policy

It is well known that certain system structures, such as a central buffer, input/output bins, and non-unit buffer capacities, eliminate the possibility of deadlock-free unsafe states (Lawley & Reveliotis, 2001). In these systems, every state is either deadlock or safe, and therefore, a single-step look-ahead policy (SSL) is a correct and optimal deadlock avoidance policy. Further, it is of polynomial complexity, and thus ideal for runtime applications in real systems. In the following, we will modify the SSL presented by Lawley (1999) so that it works with systems with multiple unreliable resources.

A resource allocation graph (RAG) is a digraph that encodes the resource requests and allocations of parts (Lawley, 1999). For our purposes, let \( RAG = (R \setminus R^{FD}, E) \) where \( R \setminus R^{FD} \) is the set of system non-failure-dependent resource types and \( E = \{(r_u, r_v): r_u, r_v \in R \setminus R^{FD} \} \) and \( r_0 \) is holding a part \( p_{jk} \) with \( p_{jk}(p_{jk+1}) = r_1 \). A subdigraph of RAG, say \((R, E)\), is induced when \( R \subseteq R \setminus R^{FD} \) and \( E = \{(r_u, r_v): (r_u, r_v) \in E \text{ and } r_u, r_v \in R \} \). A subdigraph, \( (R, E) \), forms a knot in RAG if \( \forall r_0 \in R \), \( \Gamma(r_0) = R \), where \( \Gamma(r_0) \) is the set of all nodes reachable from \( r_0 \) in RAG. In other words, a set of nodes, \( R \), forms a knot in RAG when, for every node in \( R \), the set of nodes reachable along arcs in RAG is exactly \( R \). Further, we define a capacitated knot to be a knot in which every resource in the knot is filled to capacity with parts requesting other resources in the knot. It is commonly known that a capacitated knot in RAG is a necessary and sufficient condition for deadlock in these types of sequential resource allocation systems. We now provide an algorithm, Algorithm A2, below to detect a capacitated knot in \( RAG = (R \setminus R^{FD}, E) \). This algorithm has the same polynomial complexity as that given by Lawley (1999).

**Algorithm A2:**

**Input:** \( RAG = (R \setminus R^{FD}, E) \)

**Output:** DEADLOCK, NO DEADLOCK

**Step 1:** Compute the set of strongly connected components of RAG: \( C = \{C_1, \ldots, C_q\} \)

**Step 2:** Construct digraph \( (C, E_C) \) such that \( C = \{C_1, \ldots, C_q\} \) and \( E_C = \{(C_i, C_j): (r_u, r_v) \in E \text{ with } r_u \in C_i \text{ and } r_v \in C_j \text{ for } i \neq j\} \)

**Step 3:** For every strongly connected component \( C_i \in C \) such that \( (C_i, C_j) \notin E_C \text{ for } j = 1 \ldots q \)

- If \( C_i \) is a capacitated knot
  - Return DEADLOCK
- End If

**End For**

**Step 4:** Return NO DEADLOCK

We note that, for our present work, this version of deadlock detection algorithm operates only on non-failure-dependent resources and parts held by these resources. In A2, Step 1 computes the set of strongly connected components in RAG. As mentioned earlier, this is a standard digraph operation. Step 2 constructs a digraph that defines the reachability relationship between these components. Step 3 looks for a component with no outgoing arc. If such a component is filled to capacity with parts requesting other resources in the component, then it is a capacitated knot, and deadlock exists. If no such capacitated knot exists then the RAG is deadlock-free.

Note that A2 is not correct by itself since it considers only the non-failure-dependent resources. Failure-dependent resources can easily deadlock themselves. However, when A2 is taken in conjunction with NHC, it guarantees Property 2.2 and thus assures that the system will continue to operate even when multiple unreliable resources are down.
Definition 3.1.2: Supervisor $\Delta_2 = A_2 \land NHC$.

Supervisor $\Delta_2$ accepts a system state that contains no deadlock and satisfies NHC. For example, in Figure 1, suppose that every non-failure-dependent resource has non-unit capacity; that is, $C_{i}>1$, $\forall i \in R \backslash R^{FD}$ where $[r_3,r_4]$ are deadlocked. Then, $A_2$ permits any state in which no subset of parts residing on $[r_3,r_4]$ is deadlocked on $[r_3,r_4]$. If the state also satisfies NHC, then Property 2.2 is guaranteed.

Note that $\Delta_2 = A_2 \land NHC$ is suited for real-time implementation since both $A_2$ and NHC are of polynomial complexity. Chew and Lawley (2006) formally establishes that $\Delta_2$ yields a robust supervisor for systems where every part type requires in its route at most one unreliable resource.

3.2 Robust control using a resource order policy

This subsection configures a deadlock avoidance policy, resource order policy (RO), to employ this configured resource order policy in conjunction with the neighbourhood constraints of Subsection 3.1 to develop a robust controller. Consider, for configuration purposes, Figure 1. Define $RCO = R \backslash R^{FD}$ as the set of non-failure-dependent resources. Since $R^{FD} = \{r_1,r_2\}$ and $R^{FD} = \{r_7,r_8,r_9\}$, thus $RCO = \{r_5,r_6,r_7,r_8\}$. Let $\omega: RCO \rightarrow \mathbb{N}$ (the set of natural numbers) be a one to one mapping of non-failure-dependent resources ($\omega$ is the non-failure-dependent resources so that RO can be applied; $P^{FD} = \{P_i, P_2, P_3\}$; and $P^{NF} = P^{FD}$ is the set of part types not requiring any unreliable resources; hence, in Figure 1, $P^{NF} = \{P_4\}$). For each $P_i \in P^{FD}$, determine all maximal subsequences in the route of $P_i$ that do not contain failure-dependent resources. For instance, in Figure 1, $P_3 \in P^{FD}$ where $P_3$ is a set of part types $\{P_{r_3}, P_{r_3}, P_{r_4}, P_{r_5}, P_{r_6}, P_{r_7}, P_{r_8}\}$ with route $(r_3,r_5,r_6,r_4,r_7)$, the maximal subsequences in $(r_3,r_5,r_6,r_4,r_7)$ that do not contain failure-dependent resources are $(r_3,r_5)$ and $(r_3)$. To express this formally, for each $P_i \in P^{FD}$, break the route of $P_i$ into subroutes as follows:

$P_i = \{P_{w_1} \ldots P_{w_{j-1}} P_{w_j} P_{w_{j+1}} \ldots P_{w_{k-1}} P_{w_k} P_{w_{k+1}} \ldots\}, \{P_{w_1} P_{w_2} \ldots P_{w_h}\}$ being the set of part types (of $P_i$) that is processed on failure-dependent resources (that is, $(P_1) : \{k = k_1, k_2 \ldots k_{h}\} \subseteq R^{FD}$ and $(P_2) : \{k = k_1, k_2 \ldots k_{h}\} \subseteq R^{FD}$), let $P_i = \{P_{w_1} \ldots P_{w_{j-1}} P_{w_j} P_{w_{j+1}} \ldots P_{w_{k-1}} P_{w_k} P_{w_{k+1}} \ldots\}$. For each $P_i \in P^{FD}$, rename $P_i = P_i$. Finally, let $P^{FD} = \{P_{j} \in P^{FD} \cup \{P_{j} : k = 1 \ldots h\} \in P^{FD}\}$. Note that in $P^{FD}$, a part type $P_{j} \in P^{FD}$ is replaced by a set of part types $\{P_{j}, P_{j} \ldots P_{j}\}$ each having a route that is a maximal segment of the route of $P_i$ not containing a failure-dependent resource.

In Figure 1, for example, $P_3$ is replaced by $P_3 = \{P_{r_3}, P_{r_3}\}$ with route $(r_3,r_3)$ and $P_3 = \{P_{r_3}, P_{r_3}\}$ with route $(r_3)$. $P_i$ is renamed $P_i$. Thus, the revised set of part types is $P^{FD} = \{P_{1} \cup \{P_{4}, P_{4}, P_{4}, P_{4}\}\}$. Note that none of the routes of part types in $P^{FD}$ contains any failure-dependent resources.

We now use $P^{FD}$ and RCO to construct a set of RO constraints as follows. For each $P_{j} = \{P_{j,1} \ldots P_{j,\lambda}\} \in P^{FD}$ and for each $P_{k} \in P_{j}^{FD}$, consider the inclusive remaining route, $\{\omega(P_{k}) \ldots \omega(P_{k,1})\}$, and its mapping. $\{\omega(P_{k}) \ldots \omega(P_{k,1})\}$. (Recall that to implement RO, the resources must be ordered. $\omega$ represents the ordering function.) If the mapping of the inclusive remaining route is strictly increasing (decreasing), then $P_{k}$ is classified as ‘right’ ('left'); if the mapping of the inclusive remaining route switches direction at some point,
then $P_{jk}$ is classified as ‘undirected.’ If $P_{jk}$ is terminal, it is ignored. For $r_{m} \in RCO$, let $\Pi^RU_{m}$ represent the set of right and undirected part type stages associated with $r_{m}$ and $\Pi^LU_{m}$, the set of left and undirected part type stages associated with $r_{m}$. In the example, consider that $\omega(r_{1})=1$, $\omega(r_{2})=2$, $\omega(r_{3})=3$, $\omega(r_{4})=4$, $\omega(r_{5})=5$, $\omega(r_{6})=6$, $\omega(r_{7})=7$, $\omega(r_{8})=8$ and $\omega(r_{9})=9$. We now have that the inclusive remaining route of $P_{33}$, $(r_{5},r_{6})$ supporting $(P_{33},P_{34}) \subseteq \Pi^U_{1}$, is strictly increasing for $\omega$, thus $P_{33}$ is classified as ‘right’ and hence $\Pi^U_{5} = \{P_{33}\}$. In the meantime, since $P_{25} \in \Pi^U_{2}$ is the terminal part type stage for $P_{25}$, $P_{25}$ is ignored. Clearly, $\Pi^U_{9} = \emptyset$. On the other hand, the inclusive remaining route of $P_{44}$, $(r_{6},r_{7})$ supporting $(P_{44},P_{25}) \subseteq \Pi^U_{1}$, is strictly decreasing for $\omega$, hence $P_{44}$ is classified as ‘left.’ The inclusive remaining route of $P_{24}$ is $(r_{6},r_{8})$, $(P_{24},P_{35}) \subseteq \Pi^U_{1}$, which is strictly decreasing for $\omega$, hence $P_{24}$ is classified as ‘left.’ Therefore, $\Pi^U_{8} = \{P_{24},P_{25}\}$. Meanwhile, since $P_{34} \in \Pi^U_{4}$ is the terminal part type stage for $P_{34}$, $P_{34}$ is ignored. It is obvious that $\Pi^U_{6} = \emptyset$. After all the part type stages are classified in this way, a constraint is generated for each pair of non-failure-dependent resources, yielding RO constraints. We now define RO constraints formally as follows.

**Definition 3.2.1:** RO$^{RCO}$ is the set of constraints:
\[
\forall r_{m}, r_{n} \in RCO \text{ such that } \omega(r_{m}) < \omega(r_{n}), \quad \sum_{P_{jk} \in \Pi^U_{m}} (X_{jk} + Y_{jk}) + \sum_{P_{jk} \in \Pi^L_{n}} (X_{jk} + Y_{jk}) < C_{m} + C_{n}
\]
where $C_{m}$ and $C_{n}$ are the respective buffer capacities of $r_{m}$ and $r_{n}$.

In the example, for $r_{5}$, $r_{6} \in RCO$, we have $(x_{33} + y_{33}) + (x_{34} + y_{34}) < 2$, recalling that $C_{5}, C_{6} = 1$. This constraint assures that for every resource allocation state that the system is visiting, the number of ‘right’ and ‘undirected’ parts occupying buffer space at $r_{5}$ plus the number of ‘left’ and ‘undirected’ parts occupying buffer space at $r_{6}$ will be less than the combined capacity of the two resources. Similar constraints are generated for the resource pairs $\{r_{3},r_{4}\}$, $\{r_{5},r_{7}\}$, $\{r_{6},r_{8}\}$ and $\{r_{4},r_{6}\}$.

We are now in the position to establish that the conjunction of RO$^{RCO}$ and NHC, call it supervisor $\Delta_{s}$, satisfies Property 2.2. Supervisor $\Delta_{s}$ is a control policy such that it disables $\alpha_{jk} \in \zeta(q)$ if $\delta(q,\alpha_{jk})$ violates either RO$^{RCO}$ or NHC. Formally, it is stated as follows.

**Definition 3.2.2:** Supervisor $\Delta_{s} = \text{RO}^{RCO} \wedge \text{NHC}$. Chew et al. (2011) establish that $\Delta_{s}$ is a robust controller for systems where every part type requires at most one unreliable resource.
3.3 Robust control using shared resource capacity
The robust supervisory control policies presented in sections 3.1-3.2 assume that parts requiring failed resources can be advanced into FD buffer. We refer this type of control policies as “absorbing” policies. This subsection relaxes this assumption because, in some systems, providing FD buffer space might be too expensive or it might be desirable to load the system more heavily with FD parts. A “distributing” type of control policy is developed and presented in this subsection. This policy distributes parts requiring failed resources throughout the buffer space of shared resources so that these distributed parts do not block the production of part types that are not requiring failed resources.

Now, the development of the “distributing” control policy, namely, RO^4 policy is discussed in details. First, based on the definitions of resource sets in the previous sections, we further define three resource regions: (1) the region of continuous operation, RCO=RF^FD U RN^FD, (2) the region of failure dependency, RFD=RF^D, and (3) the region of distribution, ROD=RF^D \ RU = RF^D \ RU = RF^D \ RN^FD. In the example system in Figure 6, we have RCO= [r_1, r_2, r_3]; RFD= [r_2, r_4, r_5, r_6, r_7, r_8]; ROD= [r_2, r_5, r_7]. RO^4 policy is the conjunction of four modified RO policies applied to different resource regions. We now define the RO constraints as follows.

**Definition 3.3.1**: RO^RCO is the set of constraints:
\[ \sum_{p_b \in \Omega_b} z_{jk} + \sum_{p_a \in \Omega_a} z_{uv} < C_g + C_h \]
where \( z_{st} = x_{st} + y_{st}, \quad r_g, r_h \in RCO and g \neq h \).

RO^RCO admits states that exhibit at most one capacitated resource in RCO.

**Definition 3.3.2**: RO^RFD is the set of constraints:
\[ \sum_{p_b \in \Omega_b \cap P^FD} z_{jk} + \sum_{p_a \in \Omega_a \cap P^FD} z_{uv} < C_g + C_h \quad \text{for} \quad r_i \in R^U \]
where \( z_{st} = x_{st} + y_{st}, \quad r_g, r_h \in RFD, \quad \text{and} \quad g \neq h \).

RO^RFD admits states for which at most one resource of RFD is capacitated with P^FD parts for each \( r_i \in R^U \). Note that it does not place any constraint on the total number of RFD resources capacitated.

**Definition 3.3.3**: RO^RFD^2 is the set of constraints
\[ \sum_{p_b \in \Omega_b \cap P^FD} z_{jk} + \sum_{p_a \in \Omega_a \cap P^FD} z_{mn} + \sum_{p_i \in \Omega_i \cap P^FD} z_{uv} < C_g + C_h + C_j \]
where \( z_{st} = x_{st} + y_{st}, \quad r_g, r_h, r_i \in RFD \) and \( g \neq h \neq j \).

RO^RFD^2 admits states for which at most two resources of RFD are capacitated with FD parts, but does not place any constraint on the total number of RFD resources capacitated.

**Definition 3.3.4**: RO^ROD is the set of constraints
\[ \sum_{p_b \in \Omega_b \cap P^FD} z_{jk} + \sum_{p_a \in \Omega_a \cap P^FD} z_{uv} < C_g + C_h \]
where \( z_{st} = x_{st} + y_{st}, \quad r_g, r_h \in ROD \) and \( g \neq h \).

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RO\textsuperscript{ROD} admits states for which at most one resource of ROD=RFD | R\textsuperscript{U} is capacitated with FD parts, although it places no constraint on the number of unreliable resources that are capacitated.

As in the example system in Figure 6, the set of constraints are as follows.

\[
\begin{align*}
\text{RO}\textsuperscript{RCO} & : z_{12} + z_{21} + z_{22} + z_{31} + z_{32} + z_{34} < 4 \\
\text{RO}\textsuperscript{RFD} & : z_{12} + z_{21} + z_{23} + z_{32} + z_{43} < 4 \\
\text{RO}\textsuperscript{RFD}\textsuperscript{2} & : z_{12} + z_{21} + z_{23} + z_{32} + z_{43} < 4 \\
\text{RO}\textsuperscript{ROD} & : z_{12} + z_{21} + z_{23} + z_{32} + z_{43} < 4
\end{align*}
\]

We are now in the position to establish that RO\textsuperscript{ROD} policy (the conjunction of RO\textsuperscript{RCO, RROD, RROD,} and RO\textsuperscript{ROD}), call it supervisor \( \Delta_4 \), satisfies Property 2.2. Supervisor \( \Delta_4 \) is a control policy such that it admits the enabled controllable event \( \alpha \) if and only if \( \delta(q, \alpha) \) satisfies RO\textsuperscript{ROD} \& RO\textsuperscript{RFD} \& RO\textsuperscript{RFD}\textsuperscript{2} \& RO\textsuperscript{ROD}. Formally, it is stated as follows.

**Definition 3.3.5:** Supervisor \( \Delta_4 = \text{RO}\textsuperscript{RCO} \& \text{RO}\textsuperscript{RFD} \& \text{RO}\textsuperscript{RFD}\textsuperscript{2} \& \text{RO}\textsuperscript{ROD} \).

The intuition behind this control policy is that it ensures that if a shared resource (i.e., a PFD resource) is filled with FD parts, at least one can be advanced out of the shared resources and, thus, out of RCO, which can then operate under RROD. Furthermore, clearing RCO of this part will not create problems in the FD resources. To summarize, RO\textsuperscript{RFD} allows states with at most one FD resource filled with parts that are FD on the same unreliable resource. RO\textsuperscript{RFD}\textsuperscript{2} allows states for which at most two FD resources are capacitated with FD parts. RO\textsuperscript{ROD} admits states for which at most one resource of ROD is capacitated with FD parts. Wang et al. (2008) establish that \( \Delta_4 \) is a robust controller for systems where every part type requires at most one unreliable resource.

### 4. Robust control for product routings with multiple unreliable resources

In Section 3, we develop robust controllers for the single unit resource allocation systems with multiple unreliable resources. These guarantee that if any subset of resources fails, parts in the system requiring failed resources do not block production of parts not requiring failed resources. To establish supervisor correctness, we assume that each part type requires at most one unreliable resource in its route. We now relax this assumption using a central buffer and present robust controllers that guarantee robust operation without assumptions
on route structure. To this end, we will construct new robust controllers in conjunction with the robust controllers, $\Delta_1$ and $\Delta_2$, developed in Subsection 3.1. The following three subsections will demonstrate the way we use a central buffer to extend $\Delta_1$ and $\Delta_2$ for systems where parts may require multiple unreliable resources.

### 4.1 Route partitioning algorithm

We now show how to use a central buffer to extend $\Delta_1$ and $\Delta_2$ for systems where parts may require multiple unreliable resources. We partition routes with multiple unreliable resources into subroutes, each of which contains one unreliable resource. A part in the last stage of a subroute can move to the first resource of the succeeding subroute or into the central buffer. With this partition, the system resembles one with at most one unreliable resource per route, allowing us to apply $\Delta_1$ and $\Delta_2$.

The route partitioning algorithm (RPA) performs this operation. It starts with the last stage and builds the subroute backwards. A subroute is extended until two unique unreliable resources are detected. Then, a new subroute is begun. We demonstrate below on $P_1$ of Figure 7.

#### Route Partitioning Algorithm (RPA)

**Algorithm Notation:** $j$, $q$, $u$ are indices and counters; $\epsilon$ is the empty list; $\Psi$ is a temporary set.

for $j=1, \ldots, |P|$

let $u=|P_j|$, $q=1$, $SP_j=\epsilon$, $\Psi=\emptyset$

while $u>0$

(a) if $\rho(P_{j0})=\Psi \cup \{\rho(P_{j0})\}$

(b) if $|\Psi|<2$, $SP_j=\text{push}(P_{j0},SP_j)$, $u=u-1$

(Note: The function 'push' takes two parameters, an object and an ordered list of objects, and inserts the object into the head of the list.)

(c) else $\Psi=\emptyset$, $q=q+1$, $SP_{j1}=\epsilon$

end while

$NS = q$ (Number of Segments for $P_j$)

For $j=1, u=|P_1|=8$, $q=1$, $SP_1=\epsilon$, $\Psi=\emptyset$. Then, $\rho(P_{18})=r_1 \notin R \cup \Psi = \{r_2, r_4, r_5, r_7\}$, execute (b):

$SP_{11}=\Psi \cup \{r_1\}$, $u=7$.

Next, $\rho(P_{17})=r_7 \in R \cup \Psi = \{r_2, r_4, r_5, r_7\}$, execute first if: $\Psi=\Psi \cup \{r_7\}=\{r_7\}$. Since $|\Psi|<2$, execute (b): $SP_{12}=\{r_7\}$, $u=6$.

Next, $\rho(P_{16})=r_6 \notin R \cup \Psi = \{r_2, r_4, r_5, r_7\}$, execute (b): $SP_{13}=\{r_6\}$ and $u=5$.

Next, $\rho(P_{15})=r_5 \in R \cup \Psi = \{r_2, r_4, r_5\}$, execute (a): $\Psi=\Psi \cup \{r_5\}=\{r_5, r_7\}$. Since $|\Psi|=2$, execute (c): $\Psi=\emptyset$, $q=2$, $SP_{12}=\epsilon$. This completes the first subroute $SP_{11}=\{r_1\}$.

Next, $u=5$, $\rho(P_{14})=r_3 \in R \cup \Psi = \{r_2, r_4, r_5, r_7\}$, execute (a): $\Psi=\Psi \cup \{r_3\}=\{r_3, r_5\}$. Since $|\Psi|<2$, execute (b): $SP_{12}=\{r_3\}$, $u=4$.

Next, $\rho(P_{13})=r_2 \in R \cup \Psi = \{r_2, r_4, r_5, r_7\}$, execute (a): $\Psi=\Psi \cup \{r_2\}=\{r_2, r_4, r_5\}$. Since $|\Psi|=2$, execute (c): $\Psi=\emptyset$, $q=3$, $SP_{13}=\epsilon$. This completes the second subroute $SP_{12}=\{r_3\}$.

Continuing as shown, RPA partitions $P_1$ into four subpart types (the remaining two are $SP_{12}=\{P_{13}, P_{14}\}$ and $SP_{14}=\{P_{11}, P_{12}\}$) with subroutes $TS_{11}=\{r_6, r_7, r_8\}$, $TS_{12}=\{r_5\}$, $TS_{13}=\{r_3, r_4\}$, and $TS_{14}=\{r_1, r_2\}$. Note that each subroute requires at most one unreliable resource, although the frequency of that resource is not limited. RPA does not affect part types whose routes require at most one unreliable resource.

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The maximum number of iterations of the RPA while loop is bounded by the number of part type stages, and thus RPA is no worse than \( O(\text{CRL} = \sum_{P \in P} |P|) \), which is polynomial in cumulative route length (CRL).

### 4.2 Central buffer constraints

The central buffer (CB) will be used to clear workstation buffer space of failure-dependent parts that have finished a subroute. If such parts have completely finished their original routes, they exit the system. Otherwise, they must have available space in the CB. This will ensure that they do not block the production of other part types.

For example, suppose the system of Figure 7 is in a state as follows: \( r_1 \) is failed with \( p_{17} \) waiting for processing; \( r_5 \) is holding a completed \( p_{15} \); and \( r_4 \) is holding a completed \( p_{14} \). Because of the blocking effect of \( p_{14} \) and \( p_{15} \), it is not possible to produce all other part types. However, if we relocate \( p_{14} \) and \( p_{15} \) to the CB, the system can continue producing \( P_2 \), \( P_3 \), and \( P_4 \). CB constraints are necessary to achieve this. For \( P_i \), we state the linear inequality:

\[
(x_{i1} + y_{i1}) + (x_{i2} + y_{i2}) + (x_{i3} + y_{i3}) + (x_{i4} + x_{i5} + y_{i5}) \leq B_i,
\]

where \( x_{ik} \) and \( y_{ik} \) are the number of finished and unfinished \( p_k \)'s at \( P_j \), \( x'_{ik} \) is the number of finished \( p_k \)'s relocated to the CB, and \( B \) is the CB space reserved for \( P_i \).

\[ R = \{r_1, r_2, r_3, r_4, r_5, r_7, r_8\} \]
\[ P = \{P_1, P_2, P_3, P_4\} \]
\[ R^U = \{r_4, r_5, r_7\} \]
\[ P_5 = \{P_{1u}, P_{1v}, ..., P_{1w}\} \]
\[ T_1 = \{r_1, r_2, r_3, r_4, r_5, r_7\} \]
\[ P_6 = \{P_{2u}, P_{2v}, ..., P_{2w}\} \]
\[ T_2 = \{r_1, r_2, r_5, r_7\} \]
\[ P_7 = \{P_{3u}, P_{3v}, ..., P_{3w}\} \]
\[ T_3 = \{r_1, r_3, r_5, r_7\} \]
\[ P_8 = \{P_{4u}, P_{4v}, P_{4w}\} \]
\[ T_4 = \{r_1, r_4, r_5, r_7\} \]
\[ C = \{C_1, C_2, ..., C_7\} = \{1, 1, 1, 1, 1, 1, 1\} \]

### Fig. 7. Example with four unreliable resources

With this constraint, finished parts \( p_{12} \), \( p_{14} \), and \( p_{15} \), for subpart types \( SP_{14} \), \( SP_{15} \), and \( SP_{12} \), respectively, can be moved to the CB. Thus, in the example, we can transfer the finished \( p_{14} \) and \( p_{15} \) to the CB, allowing \( P_2 \), \( P_3 \), and \( P_4 \) to continue production. In the meantime, we decrement \( x_{14} \) and \( x_{15} \) by 1, and increment \( x'_{14} \) and \( x'_{15} \) by 1. As an aside, we decrement \( x'_{14} \) by 1 and increment \( y_{15} \) by 1 when \( p_{14} \) advances from the CB into the buffer of \( r_5 \).

We now state the CB constraint, CBC. Let \( P^* = \{P ; P \in P \land |T_f - R^U| > 1\} \) be the set of part types that require multiple unreliable resources, and \( B \) the total capacity of the CB. For a part type \( P_i \in P^* \), let

\[
Z_1 = \sum_{P_k \in P \setminus SP_i} \left( x_{ik} + y_{ik} \right) + \sum_{P_k \in SP_i} x'_{ik}
\]
where $L_P^j$ is the set of “last” part type stages in the subparts of $P_j$ (except $SP_{i1}$, the final stage of $P_j$). For example, $L_P^1 = \{P_{12}, P_{14}, P_{15}\}$ and $L_P^3 = \{P_{32}, P_{34}, P_{36}, P_{38}\}$. In general,

$$L_P^j = \{P_{j1}, P_{j2}, \ldots, P_{jN_{j}}\}.$$  

$Z_j$ keeps track of the total number of instances of part type stages of $P_j \in P^*$ that are in the system. CBC is defined as:

$$i) \quad Z_j \leq B_j, \quad P_j \in P^*$$

(ii) \quad $\sum_{P_i \in P^*} B_i \leq B$

CBC ensures that every part in the system requiring multiple unreliable resources has capacity reserved on the CB. CBC has no more than $CRL^* |P|$ constraints and thus checking CBC computation is no worse than $O(CRL^* |P|)$, which is polynomial in stable measures of system size.

The level of $B_j$ for $P_j \in P^*$ can be fixed, in which case $B_j$ does not change; or state-based, where we periodically reallocate CB across all $P_j \in P^*$. Although we cannot preempt CB space from parts that have it reserved, we can reallocate CB space that is not reserved. One simple approach is to let $B_j = Z_j$ as long as (ii) holds. This represents a first-come-first-serve rule. Alternatively, we can solve the following assignment problem:

$$\min \sum_{i=1}^{B} \sum_{j=1}^{\left|P^*\right|} C_{ij} X_{ij} \quad (1)$$

$$\text{st.} \quad B_j = \sum_{i=1}^{B} X_{ij}, \quad j=1 \ldots |P^*| \quad (2)$$

$$Z_j \leq \sum_{i=1}^{B} X_{ij}, \quad j=1 \ldots |P^*| \quad (3)$$

$$\sum_{i=1}^{B} \sum_{j=1}^{\left|P^*\right|} X_{ij} \leq B \quad (4)$$

$$X_{ij} \in \{0,1\}, \quad i=1 \ldots B, j=1 \ldots |P^*| \quad (5)$$

Here, $X_{ij}$ is 1 if the $i^{th}$ unit of CB is assigned to $P_j \in P^*$, 0 otherwise. The objective (1) minimizes assignment cost; (2) counts the assignment to each $P_j \in P^*$; (3) assures no preemption from parts in the system; and (4) assures the CB is not over allocated. $C_{ij}$ is the cost of assigning CB space to $P_j \in P^*$. This cost could reflect production priorities or failure probabilities. This problem can be solved in polynomial time using the Hungarian Algorithm (Papadimitriou, 1982). The solution frequency is a topic for future research.

### 4.3 Robust controllers with CBC

We now define two supervisory controllers. The first is the conjunction of $\Delta_1$ and CBC; and the second is the conjunction of $\Delta_2$ and CBC. Recall that $\Delta_1$ and $\Delta_2$ are the controllers of Subsection 3.1. Formally, the extended supervisors are stated as follows.
Definition 4.3.1: Supervisor $\Delta_5 = \Delta_1 \land \text{CBC}$.

Definition 4.3.2: Supervisor $\Delta_6 = \Delta_2 \land \text{CBC}$.

The following theorems establish that these supervisors ensure robust operation.

Theorem 4.3.1: $\Delta_5$ is robust to failure of $\text{R}^U$.

Proof: The structure of the proof is as follows. We assume the system to be in an admissible state with parts requiring multiple unreliable resources, with some failed. We show that these parts can advance into the CB or into the buffer space of failure-dependent resources, where they do not block production of parts not requiring failed resources. Let $P \in \mathcal{P}^*$. The subpart types of $P_j$ constructed by RPA are $[\text{SP}_j, \text{NS}_j, \text{SP}_{j-1}, \ldots, \text{SP}_1]$. Assume that in the current state, $q$, unreliable resources in the subroutes of $P_j$ have failed and that $q$ satisfies $\Delta_5$. In the following, we want to show that under $\Delta_5$ parts of type $P_j$ do not block other part types from producing. We ignore parts of type $P_j$ in the final subroute since it is covered by $\Delta_1$. That is, $\Delta_5$ guarantees that parts in the final subroute can be advanced into the buffer space of the last resource and completed and removed from the system if the resource is operational or stored there, out of the way of part types not requiring failed resources, if it is not.

Let $\zeta_q = \{P_k \mid P_k \in \text{SP}_q, q = \text{NS}_y, (\text{NS}_y-1), \ldots, 2\}$ be the set of parts of $P_j$ in the state $q$. Let $\varphi_q = \{P_k \mid P_k \in \text{LP}_q\}$ be the set of parts of $P_j$ in the final stage of a subroute. By the definition of $\text{LP}_q$, $\varphi_q \subseteq \zeta_q$. Now, $\Delta_1$ guarantees that all parts in $\zeta_q \setminus \varphi_q$ can be advanced, perhaps through several processing steps, into the buffer spaces of resources required by stages of $\text{LP}_q$. That is, $\Delta_1$ guarantees a sequence of part movements such that the system reaches a new state, say $t$, where $\zeta_t = \varphi_t$. In state $t$, all instances of $P_j$ are at the end of a subroute. The left hand side of $\text{CBC}$ does not change in moving from state $q$ to state $t$. To see this, note that $\text{CBC}$ is only affected by parts in $\mathcal{P}^*$. Since we allow no new parts to be admitted and no part of $\mathcal{P}^*$ is required to move from one subroute to another (only to the end of the current subroute), the left-hand-side of $\text{CBC}$ does not change magnitude. Thus, the part advancement under $\Delta_1$ does not violate $\text{CBC}$. Now, $\text{CBC}$ guarantees that every part of $\zeta_q$ has capacity reserved on the CB, and any finished part of this set can be moved to the CB. Further, any unfinished part of $\zeta_q$ can be finished and moved to the CB if its resource is operational. If the associated resource is not operational, the part can be stored at its failed resource where it will not block the production of part types not requiring failed resources. Thus, all operational resources can be cleared of parts of type $P_j$. Under $\Delta_5$, the resulting state is a feasible initial state if resource repairs or additional failures occur.

Theorem 4.3.2: $\Delta_6$ is robust to failure of $\text{R}^U$.

Proof: The proof follows the same construction as Theorem 4.3.1. The main difference is in how BA and SSLA operate. Thus, $\Delta_5$ and $\Delta_6$ guarantee robust operation for systems where parts can require multiple unreliable resources. Note that if every resource is unreliable, both theorems continue to hold.

5. Conclusion and future research

Supervisory control for manufacturing systems resource allocation has been an active area of research. Significant amount of theories and algorithms have been developed to allocate resources effectively and efficiently, and to guarantee important system properties, such as system liveness, traceability, deadlock-free operations. However, a major assumption these research works are based on is that resources never fail. While resource failures in automated
manufacturing systems are inevitable, we investigate such system behaviours and control
dynamics. First, we developed the notion of robust supervisory control for automated
manufacturing systems with unreliable resources. Our objective is to allocate system buffer
space so that when an unreliable resource fails the system can continue to produce all part
types not requiring the failed resource. We established properties that such a controller must
satisfy, namely, that it ensure safety for the system given no resource failure; that it constrain
the system to feasible initial states in case of resource failure; that it ensure safety for the
system while the unreliable resource is failed; and that during resource repair it constrain the
system to states that will be feasible initial states when the repair is completed.
We then developed a variety of control policies that satisfy these robust properties.

| Taxonomy for Future Research Directions |
|----------------------------------------|
| **System Structure** | S1 | at most one unreliable resource for each part type |
| | S2 | random number of unreliable resources for each part type |
| **Central Buffer Capacity** | C1 | without central buffer |
| | C2 | with central buffer |
| **Flexible Routing** | FR1 | every part type stage can be performed by exactly one resource |
| | FR2 | every part type stage can be performed by exactly two resources |
| | ... | |
| | FRj | every part type stage can be performed by exactly j resources |
| **Robustness Level** | RB1 | no resource failures |
| | RB2 | at most one resource failure at any time |
| | RB3 | at most two resource failures at any time |
| | ... | |
| | RBi | at most i resource failures at any time |
| **Unreliable Resource Condition** | RC1 | unreliable resources fail at any time |
| | RC2 | unreliable resource failure characteristics can be estimated |
| **Application Areas** | AA1 | Manufacturing Systems |
| | AA2 | Business Processes and Workflow Management |
| | AA3 | E-Commerce |
| | AA4 | Supply Chain Management |
| | AA5 | Internet Resource Management |
| | AA6 | Transporation Systems |
| | AA7 | Healthcare Systems |

Table 1. Taxonomy for future research directions

Specifically, supervisory controllers $\Delta_1-\Delta_4$ are for systems with multiple unreliable resources
where each part type requires at most one unreliable resource. Supervisory controllers $\Delta_5-\Delta_6$
control systems for which part types may require multiple unreliable resources. Another
classification of the controllers is based on the underlying control mechanism: controllers $\Delta_1$-
$\Delta_3$ 'absorb' all parts requiring failed resources into the buffer space of failure-dependent
resources, controller $\Delta_4$ distribute parts requiring failed resources among the buffer space of shared resources, and controllers $\Delta_5 - \Delta_6$ utilize central buffer to achieve robust operations. These robust controllers assure different levels of robust system operation and impose very different operating dynamics on the system, thus affecting system performance in different ways. An extensive simulation study has been conducted and a set of implementation guidelines for choosing the best robust controller based on manufacturing system characteristics and performance objectives are developed in Wang et al. (2009).

A taxonomy is developed and presented in Table 1 to help guide future research in the area of robust supervisory control. By combining the different system structures, the presence/absence of central buffer, flexible routing capability, system robust level requirements, and unreliable resource failure characteristics, a significant amount of future research and development need to be done to address a variety of system control and performance requirements. And, although automated manufacturing systems are the context in which we develop the robust supervisory control research. We expect to expand our research to other application areas due to the similarity in resource allocation requirement and complexity in workflow management. The robust controllers we developed so far only address a small subset of the research taxonomy. For example, controller $\Delta_1$ falls in the category in the taxonomy of (S1, C1, FR1, RB2, RC1, AA1). Especially, it would be interesting and challenging to develop supervisory control policies for systems with flexible routing and for systems where the failure characteristics of resources are dynamically evolving and can be estimated through sensor monitoring and degradation modelling.

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