Toward Scheduling for Reconfigurable Manufacturing Systems

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Abstract: Reconfigurable Manufacturing Systems have been introduced in the mid 1990s as an alternative to classical dedicated or flexibles production systems. They are supposed to be more reactive and capable of evolving depending on unpredictable and high-frequency market changes induced by global market competition. While this concept has received a lot of attention in the literature, mainly at the design and conception phase of the production system, only few works are addressing the operational management of such production systems. One of the key features of reconfigurable manufacturing system is the possibility to use different configurations. The objective is to schedule operations efficiently while considering the different configurations of the system that are available. Switching from one configuration to another requires setup times. However, contrary to classical setup times that can be found in literature on scheduling problems, switching from a configuration $\boldsymbol{i}$ to $\boldsymbol{j}$ may require that some machines are stopped, and then reconfiguration goes beyond classical setups. This paper intends to formalise such a problem in the context of Flow-shop and Job-shop production systems. First results on small case instances are introduced.

Keywords: Reconfigurable Manufacturing Systems, Scheduling, Integer Linear Programming.

1. INTRODUCTION

Reconfigurable Manufacturing Systems (RMS) have been defined by Mehrabi et al. (2000) as an effective approach to deal with unpredictable and high-frequency market changes that are facing industries and has gained a lot of attention these past years (Bortolini et al., 2018). To meet such changes, the production systems must be adaptive and able to evolve in order to consider 1) changes in parts of existing products; 2) fluctuations in demands; 3) evolution in legal regulations and 4) evolution in process technology. Hence, RMS are built around key characteristics such as modularity, scalability, diagnosability, etc. Meanwhile, the scheduled operations remain partially manual including but not limited to: material handling, or carrying and processing jobs as stressed by (Napolitano, 2012). The assignment of operators to operations must include personal skills, training and experience in order to match the competences and/or functionalities required by the operations to be performed (Ferjani et al., 2017; Grosse et al., 2015). Reconfigurability is the capacity of a set of machines to be reconfigured in a period of time and both reconfigurable machine tools (RMT) and computer numerically controlled (CNC) machines are the core components of any reconfigurable manufacturing system. Machine switching delay from one configuration to another can include cleaning the working zone, loading, positioning and unloading the parts (jobs) and can imply extra costs coming from energy expenditures, equipment maintenance and labour as stressed by Borgia et al. (2013).

In RMS a solution for scheduling is composed by a set of configurations applied sequentially and thus a sequence-dependent processing time of operations and sequence dependent setup times have to be considered in such a production system. Finally, the sequential execution of operations depends on the job operation sequence that can refer to Flow-shop, Job-shop, etc. However, reconfigurations are not just setups and may involve several resources and they can have a larger impact on the production system. Including flexibility for processing operations remains possible at each step of the job-sequence.

The problem addressed in this research project is different from the one introduced in Essafi et al. (2012) since it does not encompass design and line balancing but only machine operations. More precisely, it is concerned with minimisation of the completion time of all operations (makespan) and not with the minimisation of a number of machines (stations), nor with the minimisation of the actual cost of the designed production system. Actually, the problem is close to the former vision provided by Liles and Huff (1990) who first indicated the necessity to plan and schedule efficiently operations in reconfigurable manufacturing environments. Hence, decisions taken at the operational level, such as schedules, are complementary to decisions taken at the strategic level (such as line balancing or line design at the conception phase), or tactical level such as production planning. However, if several works address planning of RMS (Bensmaine et al., 2014; Touzout & Benyoucef, 2019), very few consider scheduling which is a complex problem for RMS (Bortolini et al., 2018).

This work is dedicated to reconfigurable systems where operators assignment to machine allows to define several configurations meaning that processing time P_{ij}^{k} is the processing time of operation j of job i in configuration k. Switching from one configuration to another requires reconfiguration times. The objective is to schedule efficiently operations considering the configurations of the production system in order to minimise the makespan. As a first step toward integrating scheduling issues in RMS, this work focuses on the mathematical formalisation of the problem and introduces preliminary results obtained using a linear solver.

The rest of the paper is organised as follows. Section 2 introduces the literature review. Section 3 introduces the mathematical formalisation. Section 4 presents preliminary results, and Section 5 consists in the conclusion and presentation of future research prospects.

2. LITERATURE REVIEW

Reconfigurable manufacturing systems (RMS) have been formalised in the work of Koren et al. (1999) and these systems intend to fill the gap between Dedicated Lines, and Flexible Manufacturing Systems (FMS) (Koren, 2006). In dedicated lines, a single part is generally produced (few evolutions of the line are possible) with high production rates thanks to several tools simultaneously processing operations. High possible throughput allows low cost per part. In FMS, variety of products can be achieved thanks to CNC machines. These machines embed several features and are not designed to use several tools at the same time implying lower production rates and expensive cost of parts. RMS aim at reaching high throughput while preserving flexibility. This is possible by the capacity of the system to integrate new machines, or by changing modules on workstations. The evolution of such a system is called reconfiguration, and many reconfiguration periods may occur during the lifetime of the RMS. If this allows not to consider too much flexibility at the beginning, it also implies reconfigurations to be longer than classical FMS where modifications are mostly related to software changes. As stressed by Moghaddam et al. (2018) papers on RMS focus on analysing performances of various configurations or they concentrate on developing approaches and mathematical models for design and configuration selections. The authors introduce a two phased method in order to build the primary system configuration design and handle its necessary reconfigurations by considering demand changes. A Mixed integer linear programming approach is used to rearrange the system design by selecting the best possible transformation. However, durations of reconfigurations are not considered in their work. Hees et al. (2017) provided a production planning method using RMS which is validated in an application scenario. However, the authors do not consider scheduling or sequencing at the operational level.

Prasad and Jayswal (2018) presented an approach for reconfiguration of a multi-products line based on two consecutive phases: design and sequencing of products. In the design phase, the number of machines is computed and all resources are arranged in the best possible way. In the second phase, selection of the required reconfigurations is achieved in order to sequence products efficiently. Selection of a transformation is based on the effort for switching from the current configuration to the other one. However, no setup times or ramp-up is considered in the proposed approach. In Borisovsky et al. (2014), balancing of reconfigurable machining lines is addressed. Cycle times of workstations consider the processing of operations and sequence dependent set-up times. Hence, a scheduling problem is solved in addition to the assignment of operations to stations. However, the problem concerns the design of the initial configuration under which the system is operating and the setup times concern operations within a station, and not the reconfigurations.

As stressed by this short literature review, some papers are considering both design of RMS and sequencing of products at the station or at the system level. However, reconfigurations require time because of addition of new resources, or modifications of modules on workstations and this characteristic of RMS seems not to be largely addressed in the literature. If these reconfigurations can be considered as setup-times, reconfigurations may impact several machines, when generally one machine is affected at a time by a setup time in the scheduling literature. For instance, in Shen et al. (2018), a Flexible Job-shop is addressed considering sequence and machine dependent setup times of operations. In their review of setup times in Job-shop scheduling problems Sharma and Jain (2016) identify two types of setup times: sequence dependent and sequence independent setup times, both in the context of batch and non-batch (job) shop environments. The authors identify several perspectives in research among which sequence dependent setup times in the context of batch scheduling problems.

However, as stressed by Azab and Naderi (2015), very few papers deal with scheduling of RMS. In their research work, they addressed reconfigurations in the context of Flow-shop production systems. When a change in configuration has to be considered, the whole production system is stopped. However, if several machines may be inactive in order to operate a switch from a configuration to another, some of them may not be affected, especially in multiple pathways production systems.

Considering the above literature, the current paper aims at addressing scheduling at the operational level in Job-shop and Flow-shop reconfigurable manufacturing environments where setup-times can affect several machines simultaneously.

3. PROBLEM DESCRIPTION & MATHEMATICAL FORMULATION

The problem under study considers reconfigurable Job-shop and Flow-shop manufacturing systems where a set J of n jobs has to be scheduled $J = \{J_1, J_2 \dots J_n\}$ on a set M of m machines. Each job in J consists in a set of ordered operations $O_j = \{O_{1j}, \dots, O_{mj}\}$. The whole system operates under configurations which are similar to changing modes in scheduling. Switching from a configuration to another affects specific machines, resulting in variations in processing times of operations. Hence, each operation O_{ij} has a processing time P_{ij}^{k} where k denotes the configuration. This processing time varies from one configuration to another, since a configuration is defined by different assignments of resources (operators, materials, tools, etc.) to machines. Hence, the problem considers deeply modularity, scalability and convertibility. Contrary to setup times, configuration switches may affect several machines and a configuration switch can be operated when the concerned machines are inactive only. A reconfiguration time is required when switching from a configuration k_1 to k_2. Without lack of generality and for convenience, this reconfiguration time is supposed to be unitary in this research project. The objective is to schedule efficiently operations and configuration switches in order to minimise the completion time of the last operation on the last machine (makespan). In the following, the complete mathematical model is introduced.

The parameters are:

- M The number of machines;
- J The number of jobs to schedule;
- M_{ij} Machine required for the operation number j of job i;
- P_{ij} Processing time of the j^{th} operation;
- P Largest processing time of all operations;
- K Number of configurations;
- T Time horizon;
- R_{ij}^{k} Parameter equal to 1 if the machine k must be switch off during a reconfiguration from configuration from i to j and 0 elsewhere;
- RT_{ij}^{k} Reconfiguration Time for machine k to switch from configuration i to j (RT_{ij}^{k} = 0 if $R_{ij}^{k} = 0$ *and* RT_{ij}^{k} >0 if $R_{ij}^{k} = 1$);
- P_{ij}^{k} Processing time of job i on the machine j in the configuration k.

The variables are:

- bs_{ij}^{t} Binary variable equal to 1 if operation (i,j) starts at date t, 0 otherwise;
- be_{ij}^{t} Binary variable equal to 1 if operation (i,j) is under process at time t, 0 otherwise;
- bc_{k}^{t} Binary variable equal to 1 if the configuration k is used at time t and 0 otherwise;
- $br_{k_1k_2}^{t}$ Binary variable equal to 1 if at time t configuration is switched from configuration k_1 to k_2;
- $st_{i,j}$ Starting time of operation number j of job i;
- $ft_{i,j}$ Finishing time of operation number j of job i;
- $pt_{i,j}$ Processing time of operation number j of job i (this value depends on the configuration in progress at time t);
- C_{max} Finishing time of the last operation on the last machine (makespan).

The linear formalisation is a time based indexed formulation that avoids binary variables definition of disjunctions and that has been proven to be efficient for numerous disjunctive problems including Job-shop (Masmoudi et al., 2019).

The first line of the model (0) defines the objective, which is the minimisation of the makespan.

$$Min\ C_{max} \qquad (0)$$

Constraints (1) ensure that one and only one configuration k is used at any time t.

$$\forall t = 1..T \qquad \sum_{k=1}^{K} bc_{k}^{t} = 1 \qquad (1)$$

Constraints (2) ensure that operations O_{ij} have one starting time only. bs_{ij}^{t} is set to 1 at time t if operations starts at this moment.

$$\forall i = 1..J,\ \forall j = 1..M \qquad \sum_{t=1}^{T} bs_{ij}^{t} = 1 \qquad (2)$$

Constraints (3) define the integer variable $st_{i,j}$ that is equal to the time t in which operation O_{ij} is starting, and hence depends on variable bs_{ij}^{t}.

$$\forall i = 1..J,\ \forall j = 1..M \qquad \sum_{t=1}^{T} (t \times bs_{ij}^{t}) = st_{i,j} \qquad (3)$$

The constraints (4.1) and (4.2) define the processing time pt_{ij} of operation O_{ij}. The processing time pt_{ij} depends on the configuration k (variable bc_{k}^{t}) which is currently under process when operation O_{ij} is starting (variable bs_{ij}^{t}).

$$\forall i = 1..J,\ \forall j = 1..M,\ \forall t = 1..T \qquad \left(\sum_{k=1}^{K} P_{ij}^{k} \times bc_{k}^{t}\right) - \left(1 - bs_{ij}^{t}\right) \times P_{max} \le pt_{ij} \qquad (4.1)$$

$$\forall i = 1..J,\ \forall j = 1..M,\ \forall t = 1..T \qquad \left(\sum_{k=1}^{K} P_{ij}^{k} \times bc_{k}^{t}\right) + \left(1 - bs_{ij}^{t}\right) \times P_{max} \ge pt_{ij} \qquad (4.2)$$

Constraints (5) define the finishing date ft_{ij} of each operation O_{ij} based on both variables st_{ij} and pt_{ij}.

$$\forall i = 1..J,\ \forall j = 1..M \qquad ft_{ij} = st_{ij} + pt_{ij} \qquad (5)$$

Constraints (6.1) and (6.2) define the makespan i.e. the finishing time of the last operation on the last machine and ensure that this makespan is below the time horizon limit.

$$\forall i = 1..J,\ \forall j = 1..M \qquad C_{max} \ge ft_{i,j} \qquad (6.1)$$

$$C_{max} \le T \qquad (6.2)$$

Given a time t, constraints (7) set variables be_{ij}^{t} to 1 if the operation starts its processing at time t (variable bs_{ij}^{t}).

$$\forall i = 1..J,\ \forall j = 1..M,\ \forall t = 1..T \qquad bs_{ij}^{t} \le be_{ij}^{t} \qquad (7)$$

Constraints (8) ensure that variables be_{ij}^{t} are set to 1 during all the processing of operation O_{ij}.

$$\forall i = 1..J,\ \forall j = 1..M \qquad \sum_{t=1}^{T} be_{ij}^{t} = pt_{ij} \qquad (8)$$

Constraints (9.1) (9.2) set variables be_{ij}^{t} to 0 if the operation is not under process at time t. For all t that is lowered to st_{ij}, be_{ij}^{t} is set to 0. If t is superior to st_{ij}, be_{ij}^{t} can be valued either 0 or 1. For all t that is superior to ft_{ij}, be_{ij}^{t} is set to 0. If t is lower than ft_{ij}, be_{ij}^{t} can be valued either 0 or 1.

$$\forall i = 1..J,\ \forall j = 1..M,\ \forall t = 1..T \qquad -\left(1 - be_{ij}^{t}\right) \times T \leq t - st_{ij} \qquad (9.1)$$

$$\forall i = 1..J,\ \forall j = 1..M,\ \forall t = 1..T \qquad \left(be_{ij}^{t} - 1\right) \times T \leq ft_{ij} - t - 1 \qquad (9.2)$$

Constraints (10) define the relative order of successive operation of jobs, respecting Flow-shop and Job-shop conjunctive constraints. For all operations O_{ij} and O_{ij+1} the starting time of O_{ij+1} has to be greater than the finishing date of operation O_{ij}.

$$\forall i = 1..J,\ \forall j = 2..M,\ \forall j' = j + 1 \qquad ft_{ij} \leq st_{ij'} \qquad (10)$$

Constraints (11) ensure that only one operation is processed on each machine at any time t (disjunction constraints).

$$\forall t = 1..T,\ \forall j = 1..M \qquad \sum_{i=1}^{J} \sum_{k=1/M_{ik}=j}^{M} be_{ik}^{t} \leq 1 \qquad (11)$$

Constraints (12) ensure that operations O_{ij} that is supposed to be processed on a machine u cannot be processed at time t if a change from configuration k_1 to k_2 is operated at this moment and if this change implies machine u to be stopped.

$$\forall t = 1..T, \forall i = 1..J,\ \forall j = 1..M/u = M_{ij},\ \forall k_1 = 1..K,\ \forall k_2 = 1..K \,/\, R_{k_1k_2}^{u} = 1 \qquad be_{ij}^{t} \leq 1 - br_{k_1k_2}^{t} \qquad (12)$$

Constraints (13) ensure that binary variables $br_{k_1k_2}^{t}$ are set to 1 if a switch from configuration k_1 to k_2 is processed at time t.

$$\forall t = 2..T, \forall k_1 = 1..K, \forall k_2 = 1..K \qquad \left(bc_{k_1}^{t-1} + bc_{k_2}^{t} - 1\right) \leq br_{k_1k_2}^{t} \qquad (13)$$

Constraints (14) state that if the system does not operate under configuration k_2 ($bc_{k_2}^{t} = 0$) at time t, then no change in configuration from any other configuration to k_2 is possible. If $bc_{k_2}^{t} = 1$, then $br_{k_1k_2}^{t}$ can be equal to 1 if the switch into configuration k_2 has been achieved, or 0. If $k_2 = k_1$ the configuration time from k_1 to $k_1$is nul.

$$\forall t = 2..T,\ \forall k_1 = 1..K,\ \forall k_2 = 1..K \qquad bc_{k_2}^{t} \geq br_{k_1k_2}^{t} \qquad (14)$$

Constraints (15) state that if the system is not operating under configuration k_1 ($bc_{k_1}^{t} = 0$) at time $t - 1$, then no change in configuration from k_1 to any other configuration remains possible. If $bc_{k_1}^{t-1} = 1$, then $br_{k_1k_2}^{t}$ can be equal to 1 if the switch in configuration k_2 has just been processed, or 0.

$$\forall t = 2..T,\ \forall k_1 = 1..K,\ \forall k_2 = 1..K \qquad bc_{k_1}^{t-1} \geq br_{k_1k_2}^{t} \qquad (15)$$

Considering all these constraints, and because only one configuration is active at time t, the time horizon, for good solutions, will be divided into periods. Each one of these periods consists in a time window where the same configuration is applied for all the machines. Once all periods are defined, the problem consists in scheduling efficiently operations within the time windows of the different periods.

4. EXAMPLE AND NUMERICAL EXPERIMENTS

The experiments have been achieved on a set of 10 instances (damienlamy.com/Works/RMS/Scheduling_RMS/) that have been generated randomly and consist in 3 to 12 jobs, 3 machines, and 3 or 6 possible configurations. They have been solved using IBM ILOG CPLEX 12.7. Experiments are conducted on an Intel Xeon CPU E5-2660 at 2.60GHz under CentOS Linux.

Before presenting the first results on proposed instances, let us consider a basic example with 4 jobs (product orders) and 3 machines. Table 1, Table 2 and Table 3 give the job sequences and processing times of operations in the different configurations (in Table 1, M1(20) means that operations is processed on machine M1 during 20 time units). Table 4 gives the machine concerned by switching from one configuration to another.

Table 1. Job sequence in configuration 1

Job	1	2	3
J1	M1(20)	M2(3)	M3(4)
J2	M2(2)	M3(2)	M1(7)
J3	M3(6)	M1(100)	M2(5)
J4	M2(100)	M1(20)	M3(10)

Table 2. Job sequence in configuration 2

Job	1	2	3
J1	M1(2)	M2(3)	M3(4)
J2	M2(20)	M3(2)	M1(8)
J3	M3(6)	M1(10)	M2(5)
J4	M2(10)	M1(20)	M3(10)

Table 3. Job sequence in configuration 3

Job	1	2	3
J1	M1(20)	M2(3)	M3(5)
J2	M2(2)	M3(20)	M1(1)
J3	M3(6)	M1(3)	M2(1)
J4	M2(10)	M1(50)	M3(100)

Table 4. Definition of $\mathbf{R_{k_1k_2}^{u}}$

	1	2	3
1		(1;1;0)	(1;1;1)
2	(1;1;0)		(1;1;1)
3	(1;1;1)	(1;1;1)	

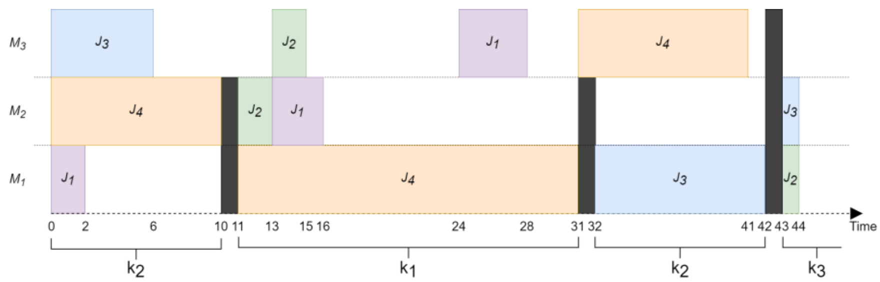

Fig. 1. One optimal solution for an instance with 4 jobs and 3 operations per job.

All machines u where the processing time is modified by a change from one configuration k_1 to k_2 is defined with $R^u_{k_1 k_2} = 1$. For example (1;1;0) on line 1 column 2, defines $R^{M_1}_{1,2} = 1$, $R^{M_2}_{1,2} = 1$ and $R^{M_3}_{1,2} = 0$. $R^{M_3}_{1,2} = 0$ means that the processing time on the machine M_3 remains identical for all operations switching from configuration 1 to 2.

According to this, if the machine M_3 is processing an operation at the time a reconfiguration occurs, it will not be affected by the reconfiguration and can continue to process a job. The optimal solution of this problem is given in Fig. 1. In this Figure, X-axis is the time axis, and each row corresponds to the operations scheduled on each machine. This figure displays all processing operations and 3 operations modelling the reconfiguration time. Hence, four periods are defined starting with configuration 2 from time 0 to 10. After a reconfiguration of 1 time unit, the system operates with configuration 1 from time 11 to 31, then configuration 2 is chosen again from time 32 to 42. This switch from configuration k_1 to k_2 implies M_1 and M_2 to be stopped during the reconfiguration, even though M_2 does not process any job after. The last configuration (k_3) is starting at time 43 and requires all machines to be stopped in order to be performed. Hence, it is not possible to anticipate the reconfiguration time of M_2 earlier. At this moment the system continues operating with configuration 3 until processing all operations and hence reaching the makespan which is valued 44. As can be stressed, when the system switches from configuration 1 to 2 the second time, machine M_3 is not affected and can start processing third operation of job J_4 at time 31.

If this example presents the principle of a solution, further results on the 10 generated instances are given in Table 5. Experiments have been achieved with a set of small scale instances with 9 operations for the smallest one (considering configurations size of problems are actually larger, i.e. Nmk(1) column) and up to 60 operations for the largest one. The solver is left running for 7200 seconds. As can be stressed from this first experiment, CPLEX has difficulties to find and prove optimality of solutions. Only four solutions are proven optimal in the dataset (S column), and five problems have no solution. Actually, no problem with more than 25 operations have solution in the given time limit. This suggests the use of other solvers such as Constrained Programming solvers, as these kind of approaches have shown great efficiency in scheduling problems (Ku & Beck, 2016) and on metaheuristics. Also the case study presented here is a static scenario. If it can be applied on a weekly planning approach, it could be extended to the dynamic situation where new product orders must be processed which would require to change configurations.

5. CONCLUSIONS

This work is at the corner stone of both scheduling community and reconfigurable manufacturing systems community since reconfigurations and setup times are very similar notions that are close to the terminology used in scheduling. The preliminary results lead us to assume that small scale instances can be solved using Linear Solvers. Considering these first results on small scale instances, the use of metaheuristics seems appropriate to address large scale problems.

Hence, current research is now directed on extending the disjunctive graph proposed in Roy and Sussmann (1964), using both repetition vector and a vector for configuration assignment. The graph encompasses disjunctive arcs for operations using the same machine and disjunctive arcs for operations in different configurations. One of the identified difficulties concern the specific structure of the longest path in order to construct different neighbourhood and guided local searches, taking advantage of structure of solutions.

Table 5. Numerical experiments with CPLEX solver

Instance	T	n	m	k	Nmk(1)	T in seconds	S
1	40	6	3	3	54	524	30*
2	25	3	3	3	27	4	17*
3	150	4	3	3	36	87	44*
4	150	8	3	3	72	7200	70
5	150	12	3	3	108	/	
6	150	4	3	6	72	1458	24*
7	150	8	3	6	144	/	
8	150	12	3	6	216	/	
9	150	8	5	3	120	/	
10	150	12	5	3	180	/	

* : optimal solution found (1) : Actual problem size because of configurations / : no solution

The current research should allow to design an algorithm for large scale instances with hundreds of operations and tens of configurations.

If this work consists in a first formalisation, it could also be interesting to address some specific features of RMS including, for instance, two types of setup times (between operations on machines, or for reconfiguration) or transportation times because of the conveyors connecting the different stations. The consideration of costs adjoined with configuration changes could also be interesting, especially to tackle scalability issues with highly, but expensive, productive configurations. Such approaches could lead to the consideration of Hybrid Flow-shop Problems. Another research prospect could be the investigation of energy efficiency of Reconfigurable Manufacturing Systems to provide solutions for switching from one configuration to another while minimising peak power constraints and/or objective. As operators with variable skills may be present in such production systems, it could also be interesting to address the problem with stochastic processing times, as reconfigurations may be postponed because of the constraint on inactivity of all machines concerned with reconfigurations. Finally, RMS are particularly suited to dynamic environments (new product orders to process or machine failures) that require to change configurations, and hence future designs of dynamic optimisation approaches are of great interest for practical industrial situations.

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