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Conference Paper

Investigation of Scheduling Techniques for Uncertain Conditions

Provided in Cooperation with:
Hamburg University of Technology (TUHH), Institute of Business Logistics and General Management

Suggested Citation: Zahid, Taiba; Kühn, Mathias; Völker, Michael; Schmidt, Thorsten (2015) : Investigation of Scheduling Techniques for Uncertain Conditions, In: Blecker, Thorsten Kersten, Wolfgang Ringle, Christian M. (Ed.): Operational Excellence in Logistics and Supply Chains: Optimization Methods, Data-driven Approaches and Security Insights. Proceedings of the Hamburg International Conference of Logistics (HICL), Vol. 22, ISBN 978-3-7375-4058-2, epubli GmbH, Berlin, pp. 171-202

This Version is available at:
https://hdl.handle.net/10419/209285

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Mitglied der Leibniz-Gemeinschaft

Proceedings of the Hamburg International Conference of Logistics (HICL) — 22

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Published in: Operational Excellence in Logistics and Supply Chains
Thorsten Blecker, Wolfgang Kersten and Christian M. Ringle (Eds.), August 2015, epubli GmbH
ISBN (online): 978-3-7375-4058-2, ISBN (print): 978-3-7375-4056-8
ISSN (online): 2365-5070, ISSN (print): 2635-4430

Investigation of Scheduling Techniques for Uncertain Conditions

Taiba Zahid, Mathias Kühn, Michael Völker and Thorsten Schmidt

The traditional methods and techniques employed in operational management seem unable to provide solutions that can be actually practiced. This insufficiency is caused by the uncertainties and delays which are faced in practice. The potential causes of these uncertainties are usually internal (inadequate resources, faults and breakdowns) and external (material shortfall or low quality) environment. These realizations have forced researchers in the past decade to find stable solutions which have ability to remain insensitive to these disturbances and provide solutions which can be practiced.

The present study investigates the methods adopted to provide such flexible and robust solutions. The aim is to identify and categorize the methodologies in this non-deterministic field and compare their performance with the static ones. In addition to that, a detail analysis of techniques proposed in the literature is delivered, which implies their limitations, assumptions and applications areas in scheduling.

Keywords: Scheduling, Uncertainty, Robustness, Stochastic

1. Introduction

The global trend towards product customization and diversification led to new requirements in production planning and control. With the consequent increasing of product complexity and variety, combined with shorter product life cycles, the uncertainty of the planning data and the frequency of disturbances increases. These fluctuations further complicate the scheduling problem which is already categorized as a NP-hard problem (Lee, 2003). Another consequence of individualization is higher product cost. To offer these products at no extra cost for the customer, improvement in planning and control is necessary. According to a recent study reported by Pekny (2005) an effective planning and scheduling system leads to a decrease in process costs as well as an increase in process throughout, implying an improvement of about 5% to 15%.

Due to increased uncertainties and disruptions along with a rise of production costs, the interest of methods for effective scheduling methods increases. In order to make the plans effective and applicable, these fluctuations at various levels of operations management need consideration at initial decision phases.

In the past decade, various researches have been conducted focusing on non-deterministic strategic analysis. We do not claim to provide an all-inclusive literature on this rapidly expanding research area, but the focus is to equip reader with a methodological investigation. This investigation summarizes the taxonomy of modelling strategies proposed in scheduling and operations management in the context of various types of fluctuations.

2. Classification of Uncertainty

The conviction of uncertainty about future is the notion known with certainty. As Hurley (1996) argued “Why is that such a vast amount of research is being conducted and financial and intellectual resources being wasted generating useless solutions to unrealistic problems?” There can be multiple causes of a disturbance with various effects resulting in the direct or indirect addition of non-value quantities. The structure of decision making typically observed in operations management (as described follows) represents a hierarchical structure characterized by distinct management requirements and thus, may exhibit peculiar reasons of disturbances.

Strategic Level: This level comprises of decisions at the earliest stage, meant for longer time horizons at managerial level. The decisions made at this level are mainly concerned with business planning. The examples can be selection of factory site, suppliers, client handlings and order collection etc.

Tactical Level: This level aims for long to midterm planning decisions. Processes are actually defined at this level and guidelines are composed. The example decisions at this stage can be budget allocation, inventory and resource distribution etc.

Operational Level: Detailed management of activities and resource allocation at production floor level is the target of operational level. This involves daily and weekly planning and management of processes.

Naturally, cause and effects of disturbances at each decision level will vary. The differentiation among these uncertainties regarding hierarchy of such decision levels helps decision makers to concentrate on specific disturbances and to model uncertainties at each specific level. Landegham and

Vanmaele (2002) summarized sources of fluctuations and their influence at each decision level in the context of demand chain planning. The final effect of disturbances although is the same i.e. a negative addition in the overall objective value of the company. However various the causes of these disturbances should be considered separately at each decision level. For example, the cause of an activity delay at operational level can be machine breakdown but the same effect of activity delay can happen due to delay in material supply at tactical level. Thus, while scheduling at operational level, decision makers need to be concerned more with the scenario of machine break down. Table 1 summarizes possible sources of uncertainty of a disturbance and their influence on various decision making levels. For example, the source of an activity delay can be caused by a delay in material supply. Although, this will affect the whole project to be delayed and will effect activities at all decision levels, but it will influence the decision making process at tactical level the most since as previously explained, this level is concerned with resource and inventory allocation decisions.

Table 1 Influence of plausible sources of disturbances on various decision making levels

Disturbance	Plausible Sources	Operational	Tactical	Strategic
Activity Delay	Machine Breakdown	High	Medium	Zero
	Resource unavailability	High	Low	Zero
	Delay in material supply	Zero	High	Medium
	Labor strike	Low	Low	High
	Limited Resources	Medium	High	Zero
Low Quality Product	Supply material error	Zero	Medium	High
	Production negligence	High	Low	Zero
	Process inefficiency	Zero	High	Medium

Disturbance	Plausible Sources	Operational	Tactical	Strategic
Cost Overshoot	Inflation in material rates	Zero	Null	High
	Resource cost Inflation	Zero	High	Low
	Order delay	High	High	Zero
Demand Fluctuation	Customer Requirements	Zero	Medium	High

Various criteria for classification of uncertainties have been proposed by researchers in order to separately identify them for modelling purposes. Subrahmanyam, Pekny and Reklaitis (1994) divided them into short term and long term uncertainties. Short term uncertainties basically comprised of shorter planning horizons and need to be dealt with on daily basis. Long term uncertainties regarded disturbances effecting decisions at strategic level such as demand fluctuations and inflation rate.

Yadegari (2013) in his work summarized the uncertainties into three types based on their frequency of occurrence named as periodic (P), sporadic (S) and unique/random (R). Periodic ones occur at regular intervals while unique occur rarely and are related with disaster management. Sporadic are the ones which occur due to the faults and errors in production planning which can be of humans as well as of machines.

In regards with supply chain problems, Geary, Childerhouse, and Towill, (2002) segregated uncertainty into process, demand, supply and control. Process uncertainties referred to the estimation of processing times for different activities. These disturbances were mainly related with the internal capacity of company to meet due dates. Fluctuations regarding delays and errors in external resources such as machinery and material were included in supply while demand uncertainties represented difference in end market demand and the orders placed by the customer. Control uncertainties spanned entire network and observed the disturbances during the entire feedback loop and information flow such as material shortage, machine breakdown, order variation and process inadequacy.

3. Modeling Strategies for Scheduling under Uncertainty

Based on these various categorizations, a number of solution strategies have been proposed for such non-deterministic scheduling strategies. Since the problems in this area are declared as NP-hard (Alcaraz, Maroto & Ruiz, 2003), researchers have focused to provide computationally effec-tive solutions. The hierarchical tree of these strategies was created after thorough investigation of literature in this area and can be visualized in figure 1. This was done in order to facilitate reader in providing a compre-hensive overview of the scattered numerous modelling strategies for this NP-Hard problem.

Broadly classifying, strategies proposed in the literature can be categorized into two major groups of proactive and reactive techniques.

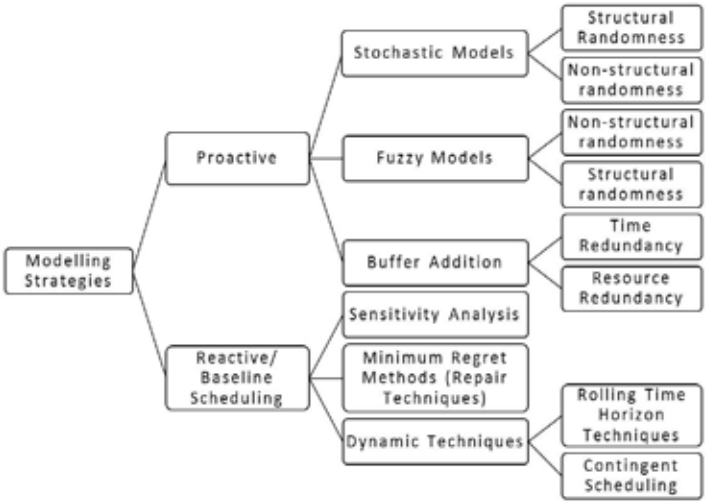

Figure 1 Taxonomy of Non-deterministic Modelling Strategies

3.1 Reactive Techniques

Reactive techniques are based on stabilizing the base line schedule in case of disturbances. A base line schedule based on deterministic information is formulized and in case of any external disruption, reactive heuristics react in such a way so as to repair the base line schedule in order to minimize the difference between base line and new schedule (minimum regret based methods). Since this technique do not requires rescheduling, the computation cost for repairing is low but results in poor results in many cases. Since reactive scheduling tend to repair the base line schedule and minimize its differences from the base line schedule, it will be more beneficial in the cases where disturbances are human based or in cases where activities can

be crashed at the expense of cost, hence in short can be summarized as manageable.

Another variation of reactive scheduling is dynamic scheduling which is further divided into two sub-strategies. As the name suggests, dynamic strategies tend to start with a feasible baseline schedule that tends to change with time to cope with disturbances caused by uncertain situations. One way is to create a feasible schedule that spans a time horizon of a year and then implement it monthly while changing the schedule of next month/time period according to the feedback of first period/month. This is known as rolling time horizon while contingent scheduling relies on creating multiple baseline schedules and shifting from one to another in case of fluctuations.

Contingent scheduling is basically a combination of reactive and proactive techniques. It focuses more towards providing flexibility rather than robustness by creating various scheduling options and adjusting the plan after realization of any disruption. This technique relies on the assumption that in a production environment, one comes across with unexpected but anticipated disruptions. Drummond, Bresina and Swanson (1994) presented way of just in case scheduling in this domain. In case of each anticipated disturbance, the schedule breaks and reschedules the rest of the activities to accommodate disturbance. Another recommendation in developing multiple baseline schedules was proposed by Billaut and Roubellat (1996). They recommended creation of groups for every renewable resource and to consider all the possible options for schedules. This was done in the hope of switching from one schedule to other in case of uncertain event. But the approach was applied on a small job shop problem and once

the problem is extended even to medium sized problems having two or more renewable resources, the number of possible options will increase to a large amount making it difficult to adopt this method.

Sensitivity analysis is mainly characterized as a post optimal tool. It mainly focuses on what-if questions from the production floor for example what is the effect of a certain parameter on optimal schedule or which data sets do not have an impact on base line schedule. Researchers mostly perform these tests on a polynomial solvable scheduling problem and then gather this data for larger scale NP-Hard problems. Hall and Posner (2004) described a detailed systematic study on the literature found on sensitivity analysis for scheduling problems. They proposed that robustness of a schedule can be improved by change of selection method for robust schedule. Apart from focusing on the best objective function value, attention should be given in selecting the schedule from the pool of near optimal schedules, which is least sensitive to external disruptions.

3.2 Proactive Techniques

Proactive techniques have been further classified into sub categories. The most popular one are stochastic techniques. Pinedo (2005) provided an overview of stochastic scheduling problems. Stochastic techniques tend to capture the uncertainties which occur periodically in the system. They require knowledge from the past and based upon this knowledge, it develops probability curves for disturbances. The quality of the solution depends upon these curves. Herroelen and Leus (2004) have given a comprehensive overview of project scheduling techniques used under uncertainty. The study mainly focuses stochastic models.

Another class of proactive scheduling is fuzzy based scheduling. These fuzzy variables are used when imprecision is observed in place of uncertainty. Mostly in case of project durations, when there is possibility of different activity durations, researchers tend to use fuzzy variables that make use of membership functions rather than probability curves. It allows managers to consider multiple possible scenarios rather than single one.

State-of-the-art literature widely discusses robust scheduling in the context of proactive strategies. But the numerous definitions and criteria of robustness have been defined which makes it difficult and rather confusing for the readers to actually state its taxonomy.

Many researchers have defined robustness in context of flexibility and quality and most of these definitions are published in machine scheduling area. Davenport and Beck (2000) defined robustness as “schedule that is able to absorb some level of unexpected events without rescheduling”. Kouvelis, Daniels and Vairaktarakis (2000) depicted robustness as “the determination of a schedule whose performance (compared to associated optimal schedule) is relatively insensitive to the potential realization of job processing times.”

Besides robustness measures, terms like quality robustness, solution robustness or stability of robustness and flexibility are often used while describing this proactive technique. In general, term quality robustness is used where sensitivity of the schedule performance is tested regarding target function while stability or solution robustness refers to the insensitivity of the schedule with respect to objective function. Robust results are not the optimal results. Many ideas have been presented to control degree of conservatism searching for the optimal one.

Through these various definitions, it can be concluded that robustness actually defines the strength or ability of a proactive schedule to be realized successfully in case of uncertainties. Hence, it is suitable to consider it in structural randomness (paper title: robust optimization of uncertain logistics networks) which can be modelled as either a possibility (fuzzy modelling) or a probability (stochastic models) depending on the data available. As a conclusion, if input data has been analyzed well enough to assign probability functions with knowledge based data, then stochastic models can be constructed, otherwise, fuzzy models are suggested to be more accurate for linguistic variables.

4. Scope of the Study

As noticeable, literature presents various approaches for optimized or feasible solutions with different solution strategies. Among all of the solution approaches (despite considering reactive or proactive strategies) metaheuristics special genetic algorithm seems to be the most popular choice for obtaining optimal results.

However up to the knowledge, no such specific criterion has been suggested, nor any systematic study has been conducted that can help decision managers for practical applications of these techniques. The literature lacks in providing comparison of solution strategies with respect to the production environments and their layouts such as job shop or assembly lines production systems.

Moreover, problem datasets which have been utilized for evaluation vary which makes it difficult to compare the efficiency of provided techniques.

Also, datasets are based on different assumptions which make these datasets suitable for limited production examples.
The current investigation provides state-of-the-art literature review in the light of following research questions:

- What are the most widely proposed solution techniques for various modelling strategies?
- Which types of uncertainties are considered?
- Comparison of data sets (limitations and application)
- Solution strategies w.r.t production layout

5. Literature Investigation

In the recent decade, a wide range of research is being carried out in the area of operations and research management for finding practical solutions for scheduling. In the following sub sections, a literature review of such methods has been provided in reference to the research questions described in section 4. Additionally, an analysis of various datasets used for benchmarking is performed to identify their limitations and applications in the industry.

5.1 Literature Review

As described in section 3, a wide spread of modelling and solution strategies is exhibited in the area of non-deterministic scheduling practices. Table 2 provides a comparison of notable researches in this area.

In Table 3, an investigation of some recent works was made on objective functions, typically being considered in the area of operations management. It was realized that most of the works focused on makespan minimization to test their respective proposed strategies. This trend is widely seen because of the fact that as a regular objective function, the quality of proposed algorithm can be better evaluated through benchmarking and sensitivity analysis. In comparison, research work that adopts time/cost trade-off as an objective is more suitable for production layouts where crashing of an activity is directly proportional to the increase in cost, mostly measured by resource utilization. Such trade-offs strategies should be evaluated through case studies.

Table 2 Literature review

Author (Year)	Type S,R,P	Model Scheme	Solving Plan	Dataset	Level	Layout	Comments
Lambrachts, O. & Herroelen, W (2007)	S	Proactive	Heuristics/ Buffer	PSPLib	Operational	RCPSP	Expert based knowledge heuristics, lacking evaluation
Sireesha, V. & Ravishankar, N (2010)	S	Fuzzy Estimation	CPM	None Specified	General	None Specified	Only precedence constraint, Construction projects suited
Yaghounzadeh, H. & Roghanian, E (2014)	S, R	Fuzzy Estimation	CCM (Critical Chain Method)	Case Study	Strategic	Construction Projects	Random durations based on expert knowledge, Position based buffers
Perez, M. and Kuhl, M.E. (2014)	General	Stochastic PERT	Simulation optimization	None Specified	Generalized	None Specified	Optimization via simulator framework

Author (Year)	Type S,R,P	Model Scheme	Solving Plan	Dataset	Level	Layout	Comments
Ramkumar, R., Tamilarasi, A., & Devi, T (2011)	S	Fuzzy Inference Model	Priority heuristics	None Specified	Tactical	Job Shop Scheduling	Due dates and customer preferences assign via priorities
Grey, J.R. (2007)	P	Stochastic Task Insertion	Time redundancy	RanGen	Strategic/ Tactical	None Specified	Modification of Extreme Buffer Sizing approach by probability distribution
Helen, R. & Sumathi, R (2013)	S	Fuzzy Modelling	CPM with crashing	None	Operational	None specified	TCTP assuming decrease of activity duration with increased cost
Petrovic, S., Fayad, C. & Petrovic, D. (2007)	S	Fuzzy PERT	Sensitivity analysis, heuristics	None	Operational	Job Shop	Knowledge based heuristics for PERT, Analysing impact of an activity delay on project makespan

Author (Year)	Type S,R,P	Model Scheme	Solving Plan	Da-taset	Level	Lay-out	Comments
Van de Vonder, S., Ballestin, F., Demeulemeester, E. & Herroelen, W (2006)	S	Dy-namic/ Contin-gent	Priori heu-ristics	PSP-Lib	Opera-tional	RCPS P	Minimum devia-tion from base-line schedule, Multiple sched-ules creation for each disturb-ance, Computa-tionally intracta-ble
Cheng, J., Fowler, J. & Kempf, K (2012)	S	Stochas-tic task Dura-tions	Simulated Anneal-ing/Monte-Carlo	PSP-Lib	Opera-tional	Prod-uct Lay-out/ MMRC PSP	Simulation based makespan opti-mization, Nor-mally distributed task durations
Hong, T.P., Yu, K.M. & Huang, C.M. (1998)	S	Fuzzy Member-ship func-tions	Priority Heuristics	None	Opera-tional	Job Shop Sched uling	Variable activity durations with Fuzzy priority rules

Author (Year)	Type S,R,P	Model Scheme	Solving Plan	Da-taset	Level	Lay-out	Comments
Archer, S., Arma-cost, R.L. & Arma-cost, J.P.(2009)	P	Stochas-tic Task Insertion	Repair heu-ristics	None	Strate-gic/ Tacti-cal	RCPS P	Left/Right shift scheduling heu-ristics, Proposing partial buffer ad-dition CPM analy-sis tool
Fallah, M., Ashtiani, B. Ary-anezhad, M. (2010)	S	Buffer sizing	CCM lognormal distribu-tion	None	Opera-tional	None Speci-fied	Project & Feeding buffers assigned in proportion with risk scale of tasks
Lee, D.E. (2003)	S	Stochas-tic Mod-elling	Monte-Carlo Sim-ulation	RanG en	General	Con-strain ed Sched ule	Computational effort reduced via reducing non-de-terministic varia-bles

Author (Year)	Type S,R,P	Model Scheme	Solving Plan	Dataset	Level	Lay-out	Comments
Umang, N., Erera, A.L. and Bierlaire, M. (2002)	S	Robust (Scenario Creation)	Local neighbourhood search	None	Operational	Single Machine Scheduling	Minimization of difference between optimal and robust solution, using CPLEX
Rodríguez, I.G., Puente, J., Varela, R. & Vela, C.R. (2008)	S	Fuzzy Modelling	Post-optimal analysis	Benchmark	Generalized	JobShop Scheduling	Hybrid approach with GA, compared with benchmark jobshop instances
Gomes, M.C., Póvoa, A.P.B. & Novais, A.Q. (2013)	P	Reactive	Modelling & heuristics	Case Study Mould making	Tactical (Order variation)	Make-to-order Type	LP model,proposed for predictive-reactive scheduling for fresh orders

Table 3 Literature analysis in regards with objective function

Author (Year)	Objective	Layout	Solving Scheme	Comments
Gerchak, Y. (2000)	Single, Minimum Penalty Cost	Not Defined	Stochastic/ Linear preserving transformation	Task duration proportional to Production cost, Limited application
Gutjahr, C. and Wegner, S.E. (2000)	Time/Cost trade off problem	None specified, suitable for single resource constrained scheduling problems for example flow lines	Stochastic Optimization, Heuristic Branch & Bound method	Comparison of various scenarios for cost efficient scheduling
Atli, O. and Kahrahman, C. (2012)	Single, Makespan minimization	None Specified, RCPSP , suitable for construction projects	Fuzzy Activity Durations, Tabu search algorithm with priority heuristics	Knowledge based estimates of activity's durations
Chen, R.M., Wub, C.L., Wang, C.M. and Lo, S.T. (2010)	Minimal makespan	RCPSP	Particle Swarm Optimization	Deterministic Variables, Random selection of parameters for PSO is applied to escape local optima

Author (Year)	Objective	Layout	Solving Scheme	Comments
Afshar-Nadjafi, B., Karimi, H., Rahimi, A. and Khalili, S. (2013)	Single, Makespan Minimization	MSRCPSP, Process layout	Heuristics with differential evolution	Deterministic variables, Differential evolution based on stochastic optimization proves to provide comparative results for Patterson's test sets
Andreica, A. and Chira, C. (2014)	Single, Makespan minimization	MMRCPSP, Generalized	Genetic Algorithm	Two loop optimization for two decision variables i.e. mode selection & deterministic start time of tasks
Coelho, J. and Vanhoucke, M. (2011)	Single, Makespan minimization	MMRCPSP, Generalized	SAT (Boolean) Solver	Utilizes SAT solver for mode assignment problem which resembles branch and bound algorithm, deterministic, limited usage due to computational complexity by increased decision variables

5.2 Dataset Comparison

To test one's solution strategy, a few benchmark data sets have been proposed in literature. These datasets libraries are created through project generators having some fixed defined parameters. Most widely used library for benchmarking is PSPLib based on ProGen. However, there are certain limitations of network instances created via ProGen that limits its usage for practical applications. A new dataset library i.e. MMLib created by RanGen has recently become more popular as benchmarking. A detail comparison between these datasets can be studied in table 4. Renewable (R), Non-renewable (NR) and human (H) resources are categorized for input details of various datasets.

Each dataset has some parameters that make it suitable for particular applications. For example, it was realized that among all, only NSPLib provides the option of personal scheduling which makes it suitable for applications where managing human resources is of foremost priority. Moreover, every production layout has specific type of input data available. Hence, a choice has to be made in selection of a particular dataset for testing purposes. However, state-of-the-art literature provides no means of comparison among these various problem generators, which makes it difficult from users point of view to decide which particular dataset would be the most suitable in a particular layout with available data information.

For the problem of job shop scheduling or for a make-to-order type environment, some special instances have been proposed by researchers. The most commonly used are Fischer & Thompson instances. A detailed comparison of these instances particularly created for such environment can be

found in (Behnke and Geiger, 2012). Following observations were made after comparing these various datasets:

- It can be perceived from gathered information that so far, there is a lack of project generators that combines personal scheduling required for special shift plans for resources and network scheduling.
- The area concerning multi-project environment requires more attention. The dataset libraries available use the concept of dummy activity for combining multiple projects that can only be applied when every project has the same start point.
- The concept of multiple modes is directed in two ways. One is multi-skilled, where an activity can be performed with different resources defined as mode options. However, datasets with alternative paths for activities (i.e. variable precedence constraints) has not been investigated so far.

Table 4 Comparison of Available Datasets

Dataset Library	PG	Creator	Availa-bility PG	Res Typ	MMA	MMS	Tasks limit	MP	Comments
MMLIB, RG300	RanGen	Demeulemeester, E., Vanhoucke, M. & Herroelen, W. (2003)	Yes	R	No	Yes	150 (max)	No	Two different libraries available,single & multimode options
PSPLib	ProGen (PSPLib)	Kolisch, R. and Sprecher, A. (1996)	No	R, NR	No	Yes	120 (max)	No	Generator not available, available dataset library with benchmarks, most widely used
Multi-project Instances	Multi-Project Generator	Browning, T.R. & Yassine, A.A. (2010)	No	R	No	No	Not limited	Yes	To study the effect of individual projects in muti-project networks

Dataset Library	PG	Creator	Avail-ability PG	ResTyp	MMA	MMS	Tasks limit	MP	Comments
Boc-tor's data set	RanGen	Boctor, F.F. (1993)	No	R	No	Yes	100 (max)	No	Resource strength is very low provided almost no re-source limits
Patter-son's test set	Cus-tomized	Patter-son, J. (1984)	No	R	No	No	50 (max)	No	Multi-resource problems by Patterson for exact heuris-tics compari-son
User Defined	P2 En-gine	Demeulemeester, E. & Vanhoucke, M. (2012)	Yes, Lim-ited	R, NR	No	No	Not limited	No	Several criteria available for defining net-work complex-ity

6. Conclusion & Future Recommendations

The current study indicates that as competitiveness at technological, qualitative and cost level acts as the main driving force, research in the area of operations management aims towards providing flexible solutions; insensitive to disruptions. The main disturbances considered in the state-of-the-art literature are activity durations and addition of tasks and are mostly dealt at operational level. The area of research, which considers the effect of possible external contributors to disturbances e.g. quality of supplies, environment and customer's demands, seems void. Moreover, it was seen that literature on periodic task insertion uncertainties prefers the utilization of reactive techniques over proactive techniques. For examining the quality of solutions, various benchmarks based on different project generators are available. However, the link between theories and industrial practices was found to be missing. Benchmarks available suggest no measures on dealing with personal scheduling problem within the context of manufacturing environment. A separate dataset named as NSPLib, specifically deals with staff scheduling problem.

Future studies in the working group of facility planning under the chair of logistics engineering at Technical University of Dresden are to be extended in a direction that provides measures to model these solutions for industrial practices. Research is being conducted for agent based optimization and robust solutions. The facility planning team focuses on implementation of efficient scheduling schemes which involve inventory management, resource allocation and plant planning. This requires the extension of resource scheduling problem (typically personal scheduling) in parallel with

production requirements. Additionally, proposal of techniques for quantitative measure of external disturbances would be beneficial in order to have better practical solutions.

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