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A state-of-art review and a simple meta-analysis on deterministic scheduling of diffusion furnaces in semiconductor manufacturing

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ABSTRACT
This paper provides a systematic review of research works on deterministic scheduling of diffusion furnaces (D-SDF) in the semiconductor manufacturing industry. After our screening process, we have identified 72 research articles published during the period 1992 to 2021 in various journals, conference proceedings, etc. This study proposes various classification schemes to systematically organise all the identified studies and to get micro-level details of D-SDF research. Further, various simple meta-analyses in the form of summary counts and percentages are carried out w.r.t (a) proposed classification schemes, and (b) various parameters such as data source, the maximum number of jobs in the instances, benchmark procedure considered, number of articles published, number of contributed authors over the years, top researchers in terms of number of publications, highly cited articles, publication outlets and publishers. From the detailed review analyses, this study suggests/shows future research opportunities/unexplored research problems considering problem configuration/objective(s)/solution methodologies in D-SDF research. Further, mapping of all references of 72 papers on D-SDF w.r.t. proposed classifications schemes would ease new researchers in D-SDF, in multiple perspectives. Finally, meta-analyses presented based on proposed classification schemes and various parameters, considered related to D-SDF problem, provide many important inferences to related researchers.

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KEYWORDS
Diffusion furnaces; semiconductor manufacturing industry; deterministic scheduling; classification schemes; meta-analysis

1. Introduction

Scheduling pertains to establishing the timing of the use of specific resources of an organisation. It occurs in every organisation, regardless of the nature of its activities Stevenson (2017). There is an ample amount of research studies reported in the literature on scheduling to achieve their goals and priorities in the available time, optimally or efficiently. Given such massive research studies, getting relevant information is like searching for a needle in a haystack for novice researchers. Further, reviewing the literature from scratch requires immense time. Hence, organizing/summarizing the existing published research in a systematic way is very useful. Accordingly, many experts reviewed the literature in various aspects of scheduling. More broadly, scheduling research can be classified with respect to its application as (i) scheduling in manufacturing, (ii) scheduling in human resource, and (iii) scheduling in computing. As this study is related to scheduling in manufacturing, scheduling in human resource and scheduling in computing are not discussed here. However, readers can refer to Borba *et al.* (2019) to know one example of scheduling in human resource (that is workforce scheduling on power utilities), and refer to Rajak and Shukla (2020) to know one example of scheduling in computing (that is, task scheduling algorithms in cloud computing).

Scheduling began to be taken seriously in the manufacturing industry at the beginning of the twentieth century with the work of Henry Gantt and other pioneers. It plays a crucial role in manufacturing industries to (a) efficiently utilise the resources, (b) meet the shipping dates, and (c) improve the production rate. Depending on the types of products manufactured the scheduling in the manufacturing industry can be classified into scheduling in discrete parts manufacturing industry (Example: Aircraft industry, Automobile industry, Semiconductor manufacturing industry) and scheduling in continuous product manufacturing industry (Example: Chemical industry, Oil refinery industry, Pulp and paper industry). As this study is concerned with scheduling in the discrete parts manufacturing industry, this study carried out the literature review only on scheduling in the discrete parts manufacturing industry.

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Further, based on the life cycle of the discrete parts manufactured products, scheduling in discrete parts manufacturing industry can be classified into short-term life cycle product manufacturing industry (Example: Semiconductor manufacturing industry, Computer manufacturing industry, Electronics manufacturing industry) and long-term life cycle product manufacturing industry (Example: Aircraft industry, Automobile industry, Steel casting industry). The scheduling is very important in the short-term life cycle product manufacturing industry than the long-term life cycle product manufacturing industry for delivering the product before the competitor win and before it becomes obsolete. So, this study focuses on the short-term life cycle product manufacturing industry, particularly the Semiconductor Manufacturing (SM) industry because the SM industry is a pivotal player in almost every industry sector.

The entire SM process is grouped into four stages: Wafer Fabrication, Wafer Probing, Assembly, and Final Testing. In the SM process, wafer fabrication and wafer probing together constitute the front-end process. The assembly and final testing constitute the back-end process. The front-end of SM contributes 90% of the capital cost, and 80% of the lead-time of manufacturing (Leachman (2002)). Further, from the technological point of view, the manufacturing process in the front-end is more complex (Quadt (2004)). Thus, this study focuses on scheduling in the front-end. However, readers interested in scheduling in the back-end can refer to Feng et al. (2020), Mathirajan, Bhargav, and Ramachandran (2010), for a good starting point in this area.

Scheduling in the front-end of the SM can be classified further into scheduling in the wafer fabrication stage, and scheduling in the wafer probing stage. Scheduling is very important in the wafer fabrication stage due to complex operations involving multiple discrete processors and batch processors with re-entrant. Further, the wafer fabrication area takes a total of 3 to 15 weeks in comparison with the required overall processing time of 8 to 30 weeks for SM (Qi (2005)). Hence, this study starts to review scheduling in wafer fabrication, and the research issues related to scheduling in the wafer probing stage (Ex: Chang and Li (2013), Huang and Lin (1998)) is not discussed here.

Some operations in wafer fabrication require 15 minutes or less to process a job, while others may require over 12 hours. The longer processing times often belong to processes on Batch Processing Machines (BPM), an expensive machine. There are many BPMs in wafer fabrication such as Oxidation, Diffusion, Deposition, E-beam writing, and Etching. Due to the longest processing time requirement, the BPM is often bottlenecking in wafer fabrication and the scheduling of a BPM is significant to improve the performance of the SM industry in general, particularly the wafer fabrication (Monch and Roob (2018)).

Though there are many BPMs in wafer fabrication, this study focuses only on the diffusion furnace because around 30% of the total WIP (work-in-process) in a wafer fabrication is staying in the diffusion area due to its lengthiest processing time among all the operations in the wafer fabrication (Jung et al. (2014)). There are many published research articles on the scheduling of diffusion furnaces (SDF). In that, most of the research studies assumed the deterministic situation, and few studies considered the stochastic situation. The assumption on the deterministic situation in SDF is being justified by the researchers mainly due to (a) the longest processing time requirement of diffusion operation and (b) the computerised shop floor environment of wafer fabrication. Due to that, any occurrences of stochastic/uncertain event(s) can be taken care of by updating the required input, particularly those that are getting affected by the stochastic/uncertain event(s), for SDF. Hence, in this study, we present a state-of-art review of all existing literature and various simple meta-analyses on the deterministic scheduling of diffusion furnaces (D-SDF) only.

The primary purpose of this study is to (i) systematically review the D-SDF research articles based on the proposed classification schemes, and (ii) conduct meta-analyses based on (a) proposed classification schemes, and (b) various parameters such as data source, maximum size (maximum number of jobs) in the instances, benchmark procedure considered, number of articles published, number of contributed authors over the years, top researchers in terms of number of publications, highly cited articles, publication outlets, publishers, etc., to suggest *and/or* bring to light some unexplored research problems, and to know the current research trends & future research directions on D-SDF research.

The rest of the paper is organised as follows. The research methodology followed to address the objective of the study is discussed in Section 2. The section 3 presents the existing research studies on the D-SDF, which are organised/summarised into various classification schemes, proposed in this study. Various simple meta-analyses considering the proposed classification schemes and other parameters are presented in Section 4. Finally, section 5 presents the summary and conclusions based on the state-of-art review of D-SDF research and various simple meta-analyses carried out in this study.

2. Research methodology

When a large body of research studies are available in an area of research, such as D-SDF research, then the data available on that research area with respect to the research problem configurations studied, types of input-data considered, the sources of data for the study, the analysis techniques used, measurement approaches followed, the type of unit studied, and the analysis procedures considered may vary enormously.

To get a micro picture of the above available data about D-SDF research, there is a need to systematically and statistically examine the data on several research studies in an area of research. Further, so far, no attempt has been made to classify and analyse the literature on D-SDF research in the SM industry. Hence, in this study, an attempt is made to review and classify the various research studies on the D-SDF in the SM industry.

Mathirajan and Sivakumar (2006) reviewed the scheduling of BPM in the SM industry and indicated that scheduling of diffusion furnaces was started in 1991 by Glassey and Weng. Hence, this study believed that the year 1991 may be considered the starting point of SDF research in the SM industry. With this, this study collected all the SDF research studies, which are published during the period 1991 to 2021, in various journals, conference proceedings, and lecture notes in computer science, in the area of Operations/Production Management, Operations Research, Logistics Management, Scheduling, Heuristic, Semiconductor Manufacturing, Industrial Engineering, Computer Science, Manufacturing, etc. Importantly, to identify and obtain all the research studies published with respect to SDF, a detailed literature search was carried out based on 8 descriptors: *'batch processor and scheduling', 'batch processing machine and scheduling', 'batching and scheduling', 'parallel batching and scheduling', 'parallel batch processing machine and scheduling', 'batching and semiconductor', diffusion and semiconductor', 'parallel batching and wafer fabrication'.*

Our literature search ended by getting 101 research articles including remotely and indirectly connecting the SDF research. So, the full text of each article was reviewed to eliminate the articles, which are not explicitly considered 'diffusion furnace(s)' for scheduling. The screening process was further refined by eliminating the SDF research articles which are not considered deterministic environment. After these elimination processes, we have observed that though the research on SDF reported in 1991 by Glassey and Weng, which is related to stochastic SDF, the research on deterministic SDF commenced in (1992) by Ahmadi et al. Accordingly, we have identified 72 research articles directly related to the D-SDF in the SM industry, which are published from 1992 to 2021. Each of the 72 D-SDF research articles is thoroughly reviewed and the summary of these is organised by considering the following problem characteristics:

- **machine environment** (single DF/multiple DFs with homogeneous type – *that is, each of the DFs having same capacity and identical technical characteristics*/multiple DFs with heterogeneous type – *that is, each of the DFs having different capacity and identical/non-identical technical characteristics*/with machine eligibility – *that is, a set of jobs can process only in a specific DF*/without machine eligibility/DF(s) along with upstream or downstream machine – *that is, considering DFs and a machine before the DFs or DFs and a machine after the DFs for scheduling together*/DF(s) with re-entrant – *that is, a job may visit a DF more than once for different operations*)
- **job characteristics** (single family of jobs/multiple compatible job families – *jobs may be having different technical requirements with different processing time or same processing time but feasible to select a set of jobs with different technical requirements as a batch for scheduling*/multiple incompatible job families – *that is, jobs may be having different technical requirements with different processing time or same processing time but not feasible to select a set of jobs with different technical requirements as a batch for scheduling*/release time – *that is, available/arrival time of a job in front of DF(s) for processing in a DF*/due-date – *that is, a commitment date given to a customer for delivery of their completed jobs*/non-agreeable release time and due dates – *that is, job that comes early may have a longer due-date than a job that comes late and vice-versa*/agreeable release time and due-dates).
- **nature of scheduling** (static – *that is, release time of all jobs are either zero or constant*/dynamic – *that is, each job available for scheduling has different release time*)
- **dynamic real time events** (job related real time events – *that is, a sudden change(s) happened to the characterises of the jobs, waiting or expected to arrive in-front of the DFs, such as changes in due-date, changes in job-priority, changes in the expected time of the arrival of job(s), decision to cancel the job for further processing, declaring the job(s) as Hot-job(s), etc.*/resource related real time events – *that is, a sudden change(s) happened to the characterises of the resources, at the time of executing a scheduling, such as operator illness during working hours, shortage of material, defective material, tool failure, machine breakdown, etc.*)
- **objective(s) of the scheduling** (single objective – *that is, only one objective considered*/multiple objectives – *that is, more than one objective is considered and optimise all the considered objectives either one at a time as a single objective or simultaneously all the objectives*

considered/completion time-based objective(s) – *that is, organisation-perspective objective(s) such as total completion time, makespan, total flow time, etc.*/due-date based objective(s) – *that is, customer-perspective objective(s) such as number of tardy jobs, maximum lateness, total tardiness, etc.*)

- ***data source*** (real data/experimental design to generate pseudo data/randomly generated data from the real fab system/data available in the published literature)
- ***solution methodology*** (mathematical approaches/ simple heuristic approaches/meta-heuristic approaches/mathematical programming based heuristic approaches)
- ***benchmark method for performance evaluation*** (optimal solution/estimated optimal solution/lower or upper bound depending on the minimising or maximising the scheduling objective/best known solution/solution to be obtained from the earlier best-known method in the literature/relatively best solution from one of the proposed methods).

Due to the brevity of the paper size, a sample summary of 10 research papers out of 72 articles is given in Annexure 1. Using each row (related to an article or a research paper) one can easily develop a consolidated review of an article (or research paper). For example, Annexure 2 provides a consolidated review of two articles (related to the first row and 10th row in Annexure 1). This study tries to summarise the 72 D-SDF research articles, identified from the systematic literature search, to suggest/show some unexplored research problems considering problem configuration/objective(s)/solution methodologies in the D-SDF research, if any, in the SM industry. This study also carried out various simple meta-analyses to get various trends and patterns to shed a greater understanding of the development and evolution of D-SDF research and to identify potential research areas for further research & improvement. The details on these are presented in the following sections.

3. A state-of-art-review on deterministic scheduling of diffusion furnaces (D-SDF)

The 72 articles identified, as part of a systematic literature search carried out, are thoroughly analysed to understand the (a) problem configuration considered, (b) solution methodologies proposed, and (c) objective(s) considered for D-SDF. The problem configurations considered in each of the 72 D-SDF research articles differ across the problem dimensions or characteristics related to *(a) machines and (b) jobs.* Each of the 72 studies reported in the literature proposed different types of solution methodologies such as mathematical programming approach (exact approach) followed by simple to meta-heuristic method(s) or simple to meta-heuristic method(s) only or simple heuristic method(s) only for scheduling diffusion furnace(s). Further, our review analysis indicated that the reported 72 research studies either considered a single objective or multiple objectives related to completion time-based criteria and/or due-date based criteria as objective(s). With these, to systematically organise and get micro-level details on the D-SDF research, this study introduces three broad classification schemes. *The first* classification scheme is based on machine environment and nature of scheduling considered in the D-SDF research, the *second* classification scheme is based on scheduling objectives aimed in the D-SDF, and the *third* classification scheme is based on solution methodologies proposed/applied by the researchers in the D-SDF research. With these, the following sub-sections discuss the mapping of research studies against the proposed classification schemes.

3.1. A classification scheme based on machine environment and nature of scheduling

In D-SDF, some of the researchers considered (a) diffusion furnaces as a single work centre, (b) diffusion furnaces along with upstream and/or downstream operation, and (c) diffusion furnaces along with the re-entrant situation. In addition, based on the nature of scheduling, D-SDF research can also further be classified into static scheduling and dynamic scheduling. The dynamic scheduling is further classified into considering the (i) future (or dynamic) arrival of jobs, (ii) occurrences of job-related real-time events along with future arrival of jobs, and (iii) occurrences of resource-related real-time events along with future arrival of jobs, at the decision-making time epoch. Accordingly, a classification scheme 1 is developed for D-SDF and presented in Figure 1. With the proposed classification scheme 1 all the published D-SDF research can be organised and mapped into 12 [$= 3*4$] different combinations of research and the same is presented in Table 1. This table provides quick and brief details for all the related studies w.r.t. each of the 12 combinations. That is, if a researcher is trying to address a problem configuration and his/her problem configuration is exactly mapping into one of these 12 combinations then he/she can get a quick and brief details on the closely related studies for the research problem considered by the researcher. Further, from Table 1, it is observed that

- there is a rich number of studies on the scheduling of *diffusion furnace as a single work centre*. In this group, most of the studies focused on dynamic

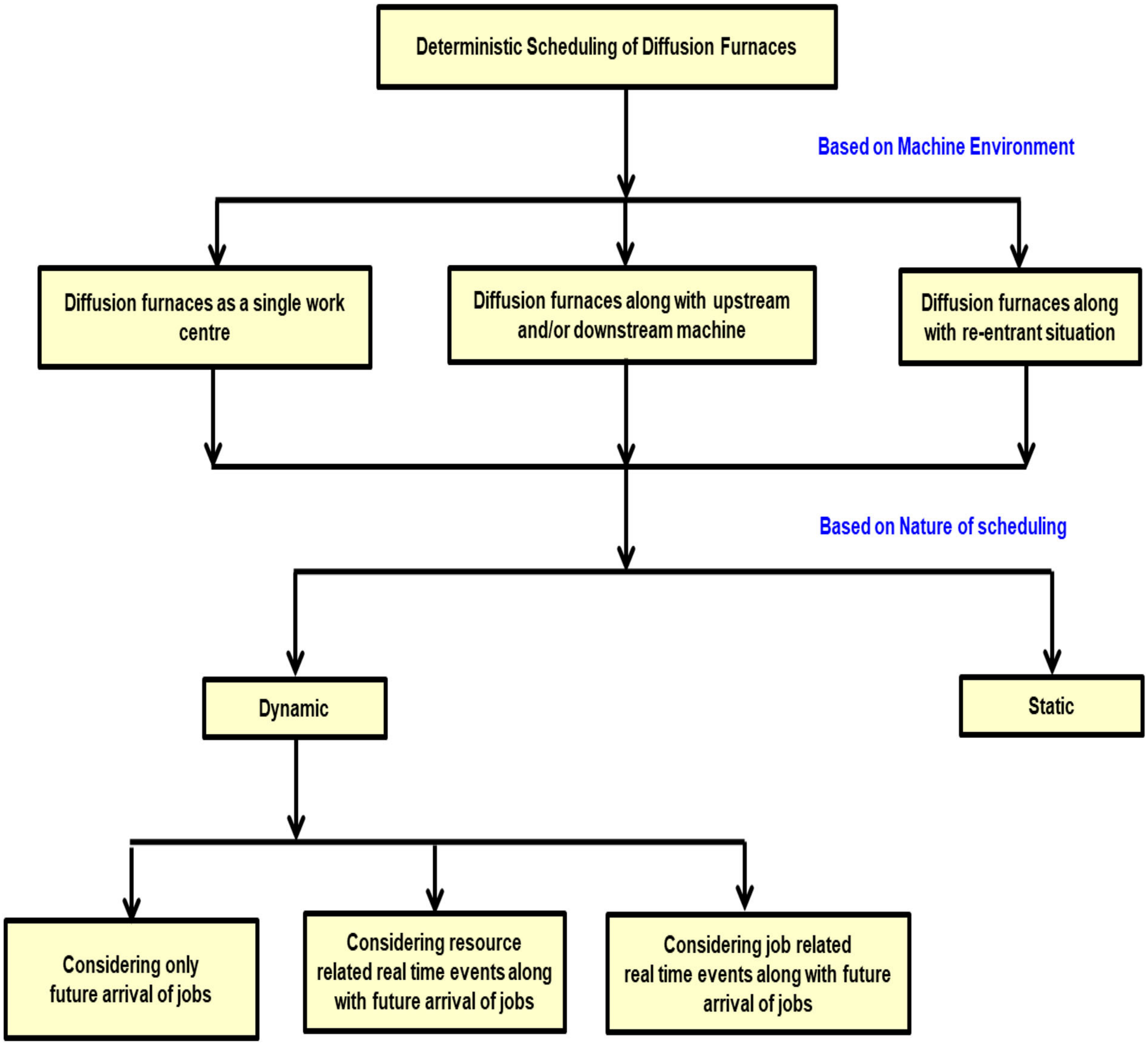

Figure 1. A classification scheme 1: based on machine environment and nature of scheduling.

scheduling. However, only a few studies considered real-time events along with the future arrival of jobs.

- only a very few researchers considered *diffusion furnaces along with one or more upstream and/or downstream operations*. Furthermore, these studies did not consider any of the real-time events.
- only a *meagre* study considered *diffusion furnaces along with the re-entrant situation* and all these studies focussed on dynamic arrival of jobs only.
- there are no reported studies in some combination of the proposed classification scheme 1, as shown in Table 1, and these are possible areas of new research in D-SDF.

As most of the research related to D-SDF considered the DF as a single work centre, and all these studies are concentrating on either static or dynamic by considering future arrival of jobs, this study believed that further decomposing the research problems on D-SDF as a single work centre by considering (a) only single DF, (b) multiple and homogeneous DFs with or without machine eligibility, and (c) multiple and heterogeneous DFs with or without machine eligibility would provide some additional details on this specific research problem.

In addition to the above grouping, these studies can be further grouped within the decomposed category based on whether the important real-life characteristic: non-agreeable release time and due-date (That is, if arrival time of job 'i' is less than the arrival time of job 'j' then it is not implied that due date of a job 'i' is less than the due date of job 'j') requirement is considered or not. With these, another classification scheme (called classification scheme 1(a)) is proposed and the same is presented in Figure 2. With classification scheme 1(a), all the existing

Table 1. Mapping of the reviewed literatures w.r.t. classification scheme 1.

Machine Environment		Nature of Scheduling	References
DF as a single work centre	Static		Mehta and Uzsoy (1998), Devpura et al. (2000), Dobson and Nambimadom (2001), Kim et al. (2001), Mönch et al. (2002), Balasubramanian et al. (2004), Perez, Fowler, and Carlyle (2005), Jolai (2005), Kashan and Karimi (2008), Monch and Almeder (2009), Almeder and Monch (2011), Dauzère-Pérès and Mönch (2013), Jung et al. (2013), Jung et al. (2014), Lausch and Mönch (2016), Jia, Wang, and Leung (2016), Monch and Roob (2018), Rocholl, Mönch, and Fowler (2020)
	Dynamic	Considering only future arrival (FA) of jobs	Uzsoy (1995), Bar-Noy et al. (2002), Kurz (2003), Mönch et al. (2005, 2006), Dirk and Monch (2006), Christian Artigues et al. (2006), Malve and Uzsoy (2007), Kurz and Mason (2008), Cheng, Chiang, and Fu (2008), Li and Qiao (2008), Cheng, Chiang, and Fu (2008), Li, Qiao, and Wu (2009), Bar-Noy et al. (2009), Chiang, Cheng, and Fu (2010), Kim, Joo, and Choi (2010), Li, Qiao, and Pan (2010), Guo, Jiang, and Hu (2010), Mathirajan and Vimalarani (2012), Shiqing Yao, Jiang, and & Li (2012), Chen et al. (2013), Bilyk, Mönch, and Almeder (2014), Paramitha Mansoer and Koo (2015), Vimala Rani and Mathirajan (2016a, 2016d), Fidelis and Arroyo (2017), Rocholl, Monch, and Fowler (2018), Rocholl, Mönch, and Fowler (2020), Vimala Rani and Mathirajan (2020a, 2020b)
		Considering job related real time events (J-RTE) along with FA of jobs	Vimala Rani and Mathirajan (2014, 2015, 2016c, 2021a, 2021b)
		Considering resource related real time events (R-RTE) along with FA of jobs	Vimala Rani and Mathirajan (2015, 2016b, 2016c, 2021a, 2021b)
Diffusion furnaces along with upstream and/or downstream machine	Static		Kim and Kim (2002), Su (2003), Sung and Kim (2003), Yugma et al. (2008), Tanju Yurtsever, Kutanoglu, and Johns (2009), Fu, Sivakumar, and Li (2012), Knopp, Dauzere-Peres, and Yugma (2014), Pirovano et al. (2020)
	Dynamic	Considering FA of jobs	Ahmadi et al. (1992), Neale and Duenyas (2000), Sung, Kim, and Yoon (2000), Yugma et al. (2012), Ham (2017), Jia et al. (2019)
		Considering J-RTE along with FA of jobs	**There is no reported study**
		Considering R-RTE along with FA of jobs	**There is no reported study**
Diffusion furnaces along with re-entrant situation	Static		**There is no reported study**
	Dynamic	Considering FA of jobs	Mason, Fowler, and Matthew (2002), Jia, Jiang, and Li (2013a), Jia, Jiang, and Li (2013b), Knopp, Dauzère-Pérès, and Yugma (2017), Wu et al. (2021)
		Considering J-RTE along with FA of jobs	**There is no reported study**
		Considering R-RTE along with FA of jobs	**There is no reported study**

research studies are mapped and presented in Table 2. Considering Table 2, one can observe the following:

- many researchers continuously put a lot of effort into scheduling single diffusion furnace and/or multiple homogeneous diffusion furnaces. However, there is very scant treatment on the scheduling of multiple heterogeneous diffusion furnaces.
- most of the studies in dynamic scheduling of single and/or multiple homogeneous diffusion furnaces consider agreeable release time and due date. Very few studies consider non-agreeable release time and due date requirement, which is one of the important problem characteristics that need to be considered in a real-life situation while scheduling a machine (a DF).
- most of the reported research studies consider the future arrival of jobs and claim as dynamic scheduling. But, in reality, dynamic scheduling includes, considering the occurrences of both future arrival of jobs and job/resource related real-time events while forming a batch to schedule in DF and there is very scant treatment has been given in the current literature on this.
- machine eligibility condition is prevailing in scheduling diffusion furnaces. However, very scant treatment has been given considering this important real-life requirement while scheduling diffusion furnaces.

3.2. A classification scheme based on scheduling objectives

The analysis of literature on D-SDF research indicated that each of the studies deals with various scheduling objectives. The scheduling objectives, in general,

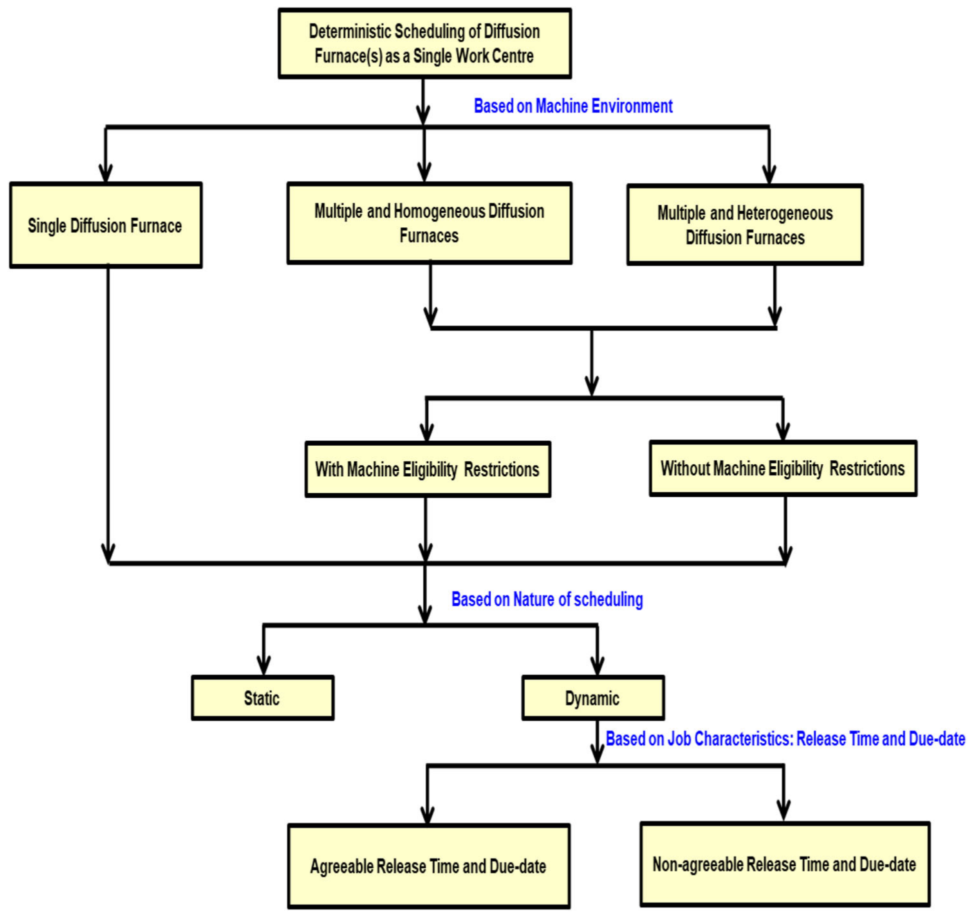

Figure 2. A classification scheme 1(a) on D-SDF.

can be classified as (a) completion time-based scheduling objective(s), and (b) due date based scheduling objective(s). Completion time based scheduling objective(s), which are organisation-perspective objective(s), will help to achieve good utilisation of machines and balance the load on machines in parallel (Pinedo (2016)). Due date based scheduling objective(s), which are customer-perspective objective(s), are important for improving on-time delivery. Accordingly, a classification scheme 2 is proposed w.r.t. scheduling objectives considered for D-SDF, and the same is presented in Figure 3.

There are many scheduling objectives, discussed in the popular textbooks on scheduling (Pinedo 2016), such as TFT (Total Flow Time), ACyT (Average Cycle Time), WACyT (Weighted Average Cycle Time), long run average time, throughput rate, work-in-process (WIP) inventory, long run average number of jobs, and discounted total weighted completion time are not considered so far in D-SDF research. However, based on the analysis of the 72 reported studies on D-SDF research, this study observed that there are 14 different types of completion time-based objectives and 11 different types of due date-based objectives are considered either as a single objective or multi objectives [optimising one objective at a time or optimising all the considered objectives simultaneously]. The earlier reported studies on D-SDF research are mapped into 25 [$= 14 + 11$] different combinations of research, and the same is presented in Table 3. In addition to that, for the benefit of the reader, we have summarised the research articles which are considering more than one objective and optimised all the considered objectives simultaneously in Annexure 3. From Table 3, it is observed the following:

- most of the D-SDF research deals with customer perspective (due date based) objectives. This could be due to the fact that delivering goods to the customer on time will enhance the customer's satisfaction and strengthen competitive advantage (Sha, Hsu, and Lai (2007)) and this is a very essential one for the products which are having short-life-cycle.
- among the customer perspective objectives, most of the studies focused on the TWT (total weighted tardiness) objective. This is probably due to the importance

Table 2. Mapping of the reviewed literatures on D-SDF as a single work centre.

Problem Configurations			References
			Single Diffusion Furnace
Static			Mehta and Uzsoy (1998), Devpura et al. (2000), Dobson and Nambimadom (2001), Perez, Fowler, and Carlyle (2005), Jolai (2005), Kashan and Karimi (2008), Dauzère-Pérès and Mönch (2013), Jung et al. (2013), Jung et al. (2014), Monch and Roob (2018)
Dynamic by considering future arrival of Jobs (D-FAJ)		Agreeable Release Time and Due-date	Uzsoy (1995), Kurz and Mason (2008), Li and Qiao (2008), Guo, Jiang, and Hu (2010), Shiqing Yao, Jiang, and & Li (2012), Paramitha Mansoer and Koo (2015)
		Non-agreeable Release Time and Due-date	Mathirajan and Vimalarani (2012), Vimala Rani and Mathirajan (2014, 2015, 2016a, 2016b, 2016c, 2016d, 2020a, 2020b, 2021a)
			Multiple and Homogeneous Diffusion Furnaces
Without machine eligibility restrictions	Static		Kim et al. (2001), Mönch et al. (2002), Balasubramanian et al. (2004), Monch and Almeder (2009), Almeder and Monch (2011), Lausch and Mönch (2016), Jia, Wang, and Leung (2016), Monch and Roob (2018), Rocholl, Mönch, and Fowler (2020)
	D-FAJ	Agreeable Release Time and Due-date	Bar-Noy et al. (2002), Kurz (2003), Mönch et al. (2005), Christian Artigues et al. (2006), Mönch, Zimmermann, and Otto (2006), Dirk and Monch (2006), Malve and Uzsoy (2007), Cheng, Chiang, and Fu (2008), Cheng, Chiang, and Fu (2008), Li, Qiao, and Wu (2009), Bar-Noy et al. (2009), Kim, Joo, and Choi (2010), Chiang, Cheng, and Fu (2010), Li, Qiao, and Pan (2010), Chen et al. (2013), Bilyk, Mönch, and Almeder (2014), Fidelis and Arroyo (2017), Rocholl, Monch, and Fowler (2018), Rocholl, Mönch, and Fowler (2020)
		Non-agreeable Release Time and Due-date	**There is no reported study**
With machine eligibility restrictions	Static		**There is no reported study**
	D-FAJ	Agreeable Release Time and Due-date	**There is no reported study**
		Non-agreeable Release Time and Due-date	**There is no reported study**
			Multiple and Heterogeneous Diffusion Furnaces
Without machine eligibility restrictions	Static		**There is no reported study**
	D-FAJ	Agreeable Release Time and Due-date	**There is no reported study**
		Non-agreeable Release Time and Due-date	**There is no reported study**
With Machine Eligibility Restrictions	Static		**There is no reported study**
	D-FAJ	Agreeable Release Time and Due-date	**There is no reported study**
		Non-agreeable Release Time and Due-date	Vimala Rani and Mathirajan (2021a, 2021b)

of avoiding the high priority jobs to be tardy. Some of the studies focussed on Tmax (Maximum Tardiness)/Lmax (Maximum Lateness), TT (Total Tardiness), NT (Number of Tardy Jobs), TEL (Total Earliness Lateness), and OTD (On Time Delivery) rate. A very few studies focussed on other due date based objectives such as weighted number of tardy jobs, weight of on time jobs, TWEL (Total Weighted Earliness Lateness), AT (Average Tardiness), and on time jobs.

- most of the researchers considered Cmax (that is, Makespan, a completion time of the last batch) as a scheduling objective, among the organisation perspective objectives, to achieve high utilisation of DF, as minimum Cmax usually implies a good utilisation (Pinedo 2016), Further, a good number of studies focused on TCT (Total Completion Time), and TWCT (Total Weighted Completion Time) scheduling objectives. Some of the studies considered the number of moves, waiting time/X-factor, batch size/ batching coefficient, violations of time window constraints/number of re-cleaned lots/machine saturation/avoid scrapped lots, cost of completing jobs/electricity power cost/electricity cost, AFT (Average Flow Time), and WCyT (Weighted Cycle Time). A very scant treatment for the completion time-based objectives such as ACT (Average Completion Time), CyT (Cycle Time), utilisation, and ANJ (Average Number of Jobs) in D-SDF research.

As most of the studies focus on due date based objectives, particularly TWT, this study further decomposed them based on machine environment and nature of scheduling to identify possible areas of new research (if any), and the same is presented in Table 4. From Table 4, it is observed that

- most of the studies considered DF as a single work center with TWT as scheduling objectives and all these studies focused on either a single furnace or

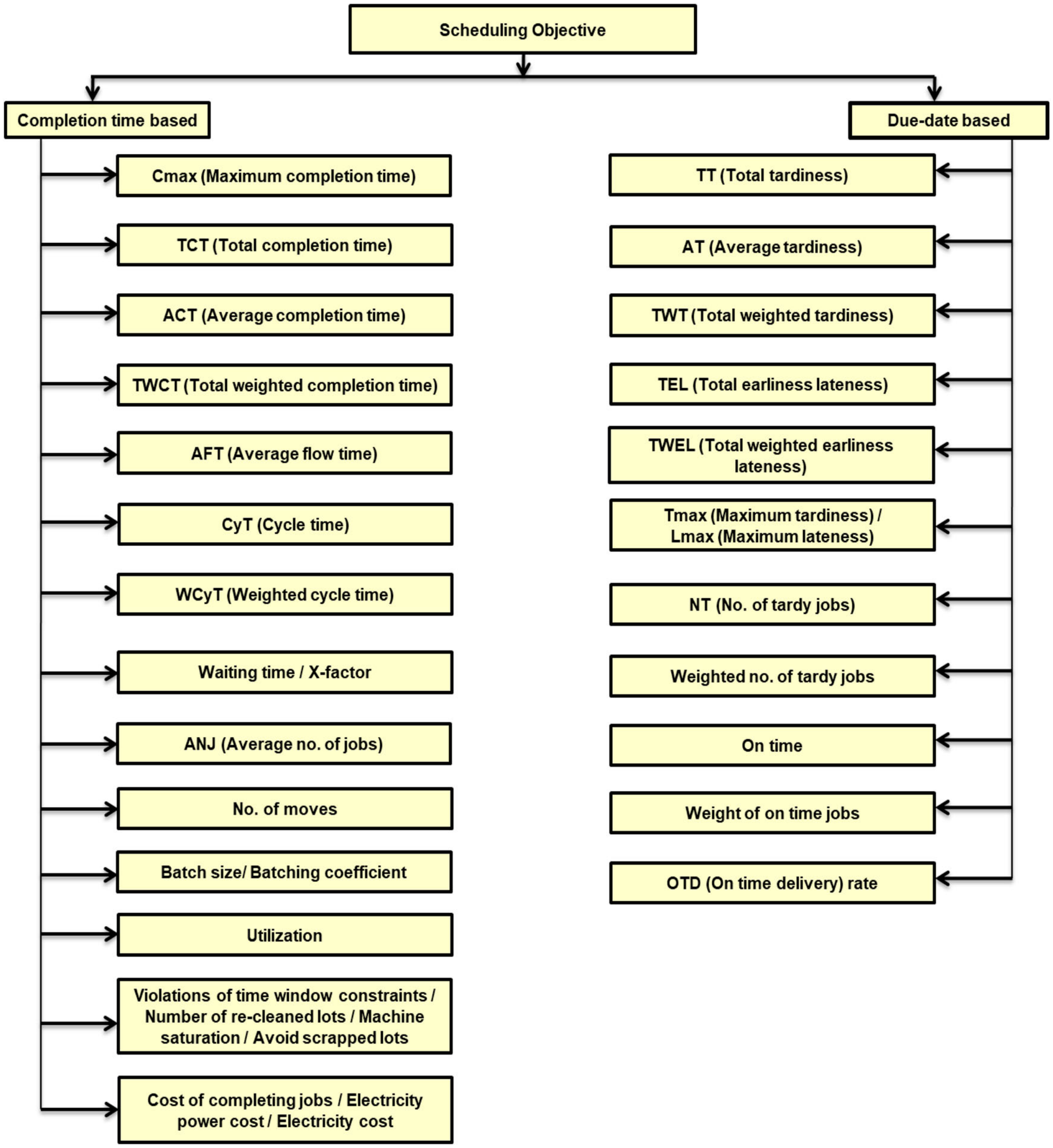

Figure 3. A classification scheme 2: based on scheduling objective in D-SDF.

multiple homogenous diffusion furnaces. A very scant treatment on multiple heterogeneous diffusion furnaces with or without machine eligibility restriction.

- there is no reported study on D-SDF along with upstream and/or downstream operations with TWT as scheduling objective and a very scant treatment on D-SDF along with the re-entrant situation with TWT as scheduling objective.
- most of the dynamic scheduling research considered only the future arrival of jobs to claim their research is related to dynamic scheduling. Very few studies considered real-time events along with the future arrival of jobs with TWT as scheduling objective for dynamic and D-SDF.

3.3. A classification scheme based on solution methodologies

Based on the solution methodologies proposed in the 72 reported studies on D-SDF, the reported studies can be broadly grouped into studies proposed/applied Mathematical programming models and Heuristic algorithm(s). The mathematical programming approach provides the optimal solution. In this group, so far Integer linear programming and Dynamic programming are proposed for D-SDF. Further, some researchers (Example: Mehta and Uzsoy (1998), Jolai (2005)) proved the computational complexity in D-SDF by developing theorems and proofs.

Table 3. Mapping of the reviewed literatures w.r.t. classification scheme 2.

	Scheduling Objectives	References
Completion time based	Cmax (Maximum completion time)	Ahmadi et al. (1992), Uzsoy (1995), Sung, Kim, and Yoon (2000), Su (2003), Dirk and Monch (2006), Li, Qiao, and Pan (2010), Chen et al. (2013), Knopp, Dauzere-Peres, and Yugma (2014), Jia, Wang, and Leung (2016), Ham (2017), Knopp, Dauzère-Pérès, and Yugma (2017)
	TCT (Total completion time)	Ahmadi et al. (1992), Neale and Duenyas (2000), Sung, Kim, and Yoon (2000), Kim and Kim (2002), Shiqing Yao, Jiang, and & Li (2012), Jia, Jiang, and Li (2013a),
	ACT (Average completion time)	Fu, Sivakumar, and Li (2012)
	TWCT (Total weighted completion time)	Uzsoy (1995), Kashan and Karimi (2008), Tanju Yurtsever, Kutanoglu, and Johns (2009), Knopp, Dauzère-Pérès, and Yugma (2017), Rocholl, Monch, and Fowler (2018), Rocholl, Mönch, and Fowler (2020)
	AFT (Average flow time)	Dobson and Nambimadom (2001), Pirovano et al. (2020)
	CyT (Cycle time)	Tanju Yurtsever, Kutanoglu, and Johns (2009)
	WCyT (Weighted cycle time)	Jung et al. (2013), Jung et al. (2014)
	Waiting time / X-factor	Christian Artigues et al. (2006), Yugma et al. (2008), Yugma et al. (2012)
	ANJ (Average no. of jobs)	Neale and Duenyas (2000)
	No. of moves	Christian Artigues et al. (2006), Yugma et al. (2008), Yugma et al. (2012), Wu et al. (2021)
	Batch size/ Batching coefficient	Christian Artigues et al. (2006), Yugma et al. (2008), Yugma et al. (2012)
	Utilisation	Tanju Yurtsever, Kutanoglu, and Johns (2009)
	Violations of time window constraints / Number of re-cleaned lots / Machine saturation / Avoid scrapped lots	Jung et al. (2013), Jung et al. (2014), Pirovano et al. (2020)
	Cost of completing jobs / Electricity power cost / Electricity cost	Monch and Roob (2018), Rocholl, Monch, and Fowler (2018), Rocholl, Mönch, and Fowler (2020)
Due-date based	TT (Total tardiness)	Mehta and Uzsoy (1998), Kim et al. (2001), Sung and Kim (2003), Kim, Joo, and Choi (2010), Jia et al. (2019), Vimala Rani and Mathirajan (2021a)
	AT (Average tardiness)	Perez, Fowler, and Carlyle (2005)
	TWT (Total weighted tardiness)	Devpura et al. (2000), Mönch et al. (2002), Mason, Fowler, and Matthew (2002), Kurz (2003), Balasubramanian et al. (2004), Perez, Fowler, and Carlyle (2005), Mönch et al. (2005), Dirk and Monch (2006), Mönch, Zimmermann, and Otto (2006), Cheng, Chiang, and Fu (2008), Li and Qiao (2008), Kurz and Mason (2008), Li, Qiao, and Wu (2009), Monch and Almeder (2009), Chiang, Cheng, and Fu (2010), Guo, Jiang, and Hu (2010), Li, Qiao, and Pan (2010), Almeder and Monch (2011), Mathirajan and Vimalarani (2012), Chen et al. (2013), Jia, Jiang, and Li (2013a, 2013b), Bilyk, Mönch, and Almeder (2014), Vimala Rani and Mathirajan (2014, 2015), Lausch and Mönch (2016), Vimala Rani and Mathirajan (2016a, 2016b, 2016c, 2016d), Fidelis and Arroyo (2017), Knopp, Dauzère-Pérès, and Yugma (2017), Monch and Roob (2018), Rocholl, Mönch, and Fowler (2020), Vimala Rani and Mathirajan (2020a, 2020b, 2021a, 2021b)
	TEL (Total earliness lateness)	Vimala Rani and Mathirajan (2016c, 2016d, 2020b, 2021a)
	TWEL (Total weighted earliness lateness)	Vimala Rani and Mathirajan (2021a)
	Tmax (Maximum tardiness)/ Lmax (Maximum lateness)	Uzsoy (1995), Sung and Kim (2003), Malve and Uzsoy (2007), Cheng, Chiang, and Fu (2008), Jia, Jiang, and Li (2013a), Vimala Rani and Mathirajan (2016c, 2016d), Knopp, Dauzère-Pérès, and Yugma (2017), Vimala Rani and Mathirajan (2020b, 2021a)
	NT (No. of tardy jobs)	Sung and Kim (2003), Jolai (2005), Vimala Rani and Mathirajan (2016c, 2016d, 2021a)
	Weighted no. of tardy jobs	Dauzère-Pérès and Mönch (2013), Monch and Roob (2018), Vimala Rani and Mathirajan (2021a)
	On time	Tanju Yurtsever, Kutanoglu, and Johns (2009)
	Weight of on time jobs	Bar-Noy et al. (2002), Bar-Noy et al. (2009)
	OTD (On time delivery) rate	Vimala Rani and Mathirajan (2016c, 2016d, 2020b, 2021a)

The proposed heuristic algorithms can be further classified into a simple heuristic algorithm, Meta-heuristic algorithm, and Mathematical programming based heuristic algorithm. All the meta-heuristics can be broadly classified into (i) single solution-based approach (Example: Simulated annealing, Tabu search), and (ii) population-based approach (Example: Genetic algorithm, Ant Colony Optimisation). Accordingly, this study proposed a classification scheme 3 based on the existing solution methodologies and presented it in Figure 4. The earlier studies identified in D-SDF research are mapped into 14 [= 3 + 1+4 + 5+1] different combinations of research, based on classification scheme 3, and the same is presented in 5.

Based on the analysis of the 72 reported studies on D-SDF, it is observed that so far four single-solution based meta-heuristics and five population-based meta-heuristics are addressed by various researchers in D-SDF research. However, there are various meta-heuristics such Bat algorithm (Dao et al. 2018), Bees algorithm (Phruek-sanant 2013), Cuckoo algorithm (Laha and Gupta 2018) proposed/applied for different problem environments in

Table 4. D-SDF Research Considering Due-Date based Objective: TWT.

Machine Environment		Nature of Scheduling		References
DF as a single work centre	Single Diffusion Furnace	Static		Devpura et al. (2000), Perez, Fowler, and Carlyle (2005), Monch and Roob (2018)
		Dynamic	Only FA of jobs	Kurz and Mason (2008), Li and Qiao (2008), Guo, Jiang, and Hu (2010), Mathirajan and Vimalarani (2012), Vimala Rani and Mathirajan (2016a, 2016d, 2020a, 2020b)
			J-RTE along with FA of jobs	Vimala Rani and Mathirajan (2014, 2015, 2016c, 2021a)
			R-RTE along with FA of jobs	Vimala Rani and Mathirajan (2015, 2016b, 2016c, 2021a)
	Multiple and Homogenous Diffusion Furnaces	Static		Mönch et al. (2002), Balasubramanian et al. (2004), Monch and Almeder (2009), Almeder and Monch (2011), Lausch and Mönch (2016), Monch and Roob (2018), Rocholl, Mönch, and Fowler (2020)
		Dynamic	Only FA of jobs	Kurz (2003), Mönch et al. (2005), Dirk and Monch (2006), Mönch, Zimmermann, and Otto (2006), Cheng, Chiang, and Fu (2008), Li, Qiao, and Wu (2009), Chiang, Cheng, and Fu (2010), Li, Qiao, and Pan (2010), Chen et al. (2013), Bilyk, Mönch, and Almeder (2014), Fidelis and Arroyo (2017), Rocholl, Mönch, and Fowler (2020)
			J-RTE along with FA of jobs	**There is no reported study**
			R-RTE along with FA of jobs	**There is no reported study**
	Multiple and Heterogeneous Diffusion Furnaces	Static		**There is no reported study**
		Dynamic	Only FA of jobs	**There is no reported study**
			J-RTE along with FA of jobs	Vimala Rani and Mathirajan (2021a, 2021b)
			R-RTE along with FA of jobs	Vimala Rani and Mathirajan (2021a, 2021b)
Diffusion furnaces along with upstream and/or downstream machine		Static		**There is no reported study**
		Dynamic	Only FA of jobs	**There is no reported study**
			J-RTE along with FA of jobs	**There is no reported study**
			R-RTE along with FA of jobs	**There is no reported study**
Diffusion furnaces along with re-entrant situation		Static		**There is no reported study**
		Dynamic	Only FA of jobs	Mason, Fowler, and Matthew (2002), Jia et al. (2013a, 2013b), Knopp, Dauzère-Pérès, and Yugma (2017)
			J-RTE along with FA of jobs	**There is no reported study**
			R-RTE along with FA of jobs	**There is no reported study**

general, particularly machine scheduling situation are yet to explore in D-SDF. All the non-explored meta-heuristics can be explored appropriately for D-SDF, as new research avenues. In addition, the following observations can be inferred from Table 5.

- The research studies, which are proposed/implemented mathematical programming approaches mostly focus on Integer linear programming than Dynamic programming.
- The mathematical approaches provide an optimal solution in (i) a reasonable time for a simple and/or smaller version of D-SDF research, and (ii) an unreasonable time for the real-life large-scale sized problems (Vimala Rani and Mathirajan 2020b). Due to the computational intractability issue in solving real-life large-sized problems in D-SDF research, the majority of the researchers proposed heuristic approaches, particularly simple heuristics to obtain an efficient solution with very reasonable computational time. Moreover, keeping in mind the computational difficulty of the scheduling problems, it is not surprising to see that many of the researchers have developed heuristics as one of the acceptable solution methodology (Ángel-Bello et al. 2011).

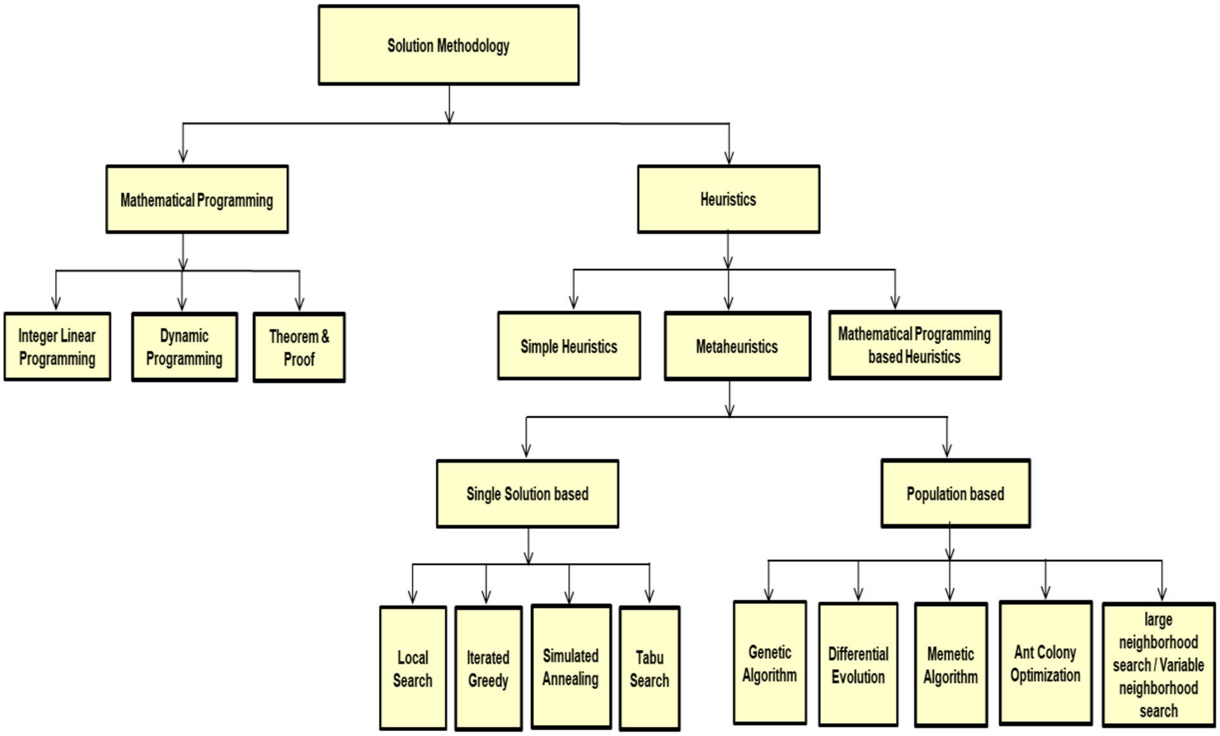

Figure 4. A classification scheme 3: based on solution methodologies w.r.t. reported studies on D-SDF.

- A few studies focused on the mathematical programming based heuristic approach for D-SDF.
- Population-based meta-heuristics are mostly implemented in D-SDF research than single solution-based meta-heuristics. Simulated annealing and Genetic algorithm are the most widely used algorithms in single solution-based and population-based meta-heuristics respectively.

As many studies proposed/implemented a simple heuristic, this study further decomposes them based on machine environment and nature of scheduling for understanding the utility of the simple heuristic, and the same is presented in Table 6. From this table, it is observed that

- Many researchers proposed a simple heuristic algorithm by considering DF as a single work center, particularly for single DF and multiple homogeneous DF. A very scant treatment on multiple heterogeneous DF with/without machine eligibility restriction.
- Few researchers proposed a heuristic algorithm by considering DF along with upstream and/or downstream operations.

Table 5. Mapping of the reviewed literatures w.r.t. classification scheme 3.

Solution Methodology		References
Mathematical Programming	Integer Linear Programming	Dobson and Nambimadom (2001), Su (2003), Christian Artigues et al. (2006), Monch and Almeder (2009), Tanju Yurtsever, Kutanoglu, and Johns (2009), Fu, Sivakumar, and Li (2012), Dauzère-Pérès and Mönch (2013), Jia, Jiang, and Li (2013a), Jung et al. (2013), Jung et al. (2014), Bilyk, Mönch, and Almeder (2014), Vimala Rani and Mathirajan (2015,2016a, 2016c, 2016d), Lausch and Mönch (2016), Jia, Wang, and Leung (2016), Ham (2017), Fidelis and Arroyo (2017), Monch and Roob (2018), Rocholl, Monch, and Fowler (2018), Jia et al. (2019), Rocholl, Mönch, and Fowler (2020), Vimala Rani and Mathirajan (2020a, 2020b), Vimala Rani and Mathirajan (2021a)
	Dynamic Programming	Mehta and Uzsoy (1998), Neale and Duenyas (2000), Sung and Kim (2003), Jolai (2005), Wu et al. (2021)
	Theorem & Proof (for computational complexity)	Mehta and Uzsoy (1998), Sung, Kim, and Yoon (2000), Dobson and Nambimadom (2001), Bar-Noy et al. (2002), Kurz (2003), Su (2003), Sung and Kim (2003), Jolai (2005), Bar-Noy et al. (2009), Fu, Sivakumar, and Li (2012), Dauzère-Pérès and Mönch (2013), Rocholl, Monch, and Fowler (2018), Wu et al. (2021)

(*continued*)

Table 5. Continued.

Solution methodology				References
		Simple Heuristics		Ahmadi et al. (1992), Uzsoy (1995), Mehta and Uzsoy (1998), Neale and Duenyas (2000), Devpura et al. (2000), Sung, Kim, and Yoon (2000), Dobson and Nambimadom (2001), Kim et al. (2001), Mason, Fowler, and Matthew (2002), Bar-Noy et al. (2002), Su (2003), Perez, Fowler, and Carlyle (2005), Mönch, Zimmermann, and Otto (2006), Dirk and Monch (2006), Christian Artigues et al. (2006), Malve and Uzsoy (2007), Kurz and Mason (2008), Cheng, Chiang, and Fu (2008), Li and Qiao (2008), Chiang, Cheng, and Fu (2008), Kashan and Karimi (2008), Yugma et al. (2008), Li, Qiao, and Wu (2009), Monch and Almeder (2009), Bar-Noy et al. (2009), Tanju Yurtsever, Kutanoglu, and Johns (2009), Chiang, Cheng, and Fu (2010), Kim, Joo, and Choi (2010), Li, Qiao, and Pan (2010), Almeder and Monch (2011), Yugma et al. (2012), Fu, Sivakumar, and Li (2012), Mathirajan and Vimalarani (2012), Jia, Jiang, and Li (2013a, 2013b), Knopp, Dauzere-Peres, and Yugma (2014), Vimala Rani and Mathirajan (2014), Bilyk, Mönch, and Almeder (2014), Paramitha Mansoer and Koo (2015), Vimala Rani and Mathirajan (2015), Lausch and Mönch (2016), Vimala Rani and Mathirajan (2016a, 2016b, 2016c), Jia, Wang, and Leung (2016), Knopp, Dauzère-Pérès, and Yugma (2017), Fidelis and Arroyo (2017), Monch and Roob (2018), Pirovano et al. (2020), Rocholl, Mönch, and Fowler (2020), Vimala Rani and Mathirajan (2020a, 2020b, 2021a, 2021b)
Heuristics	Metaheuristics	Single Solution based	Local Search	Christian Artigues et al. (2006), Knopp, Dauzère-Pérès, and Yugma (2017), Rocholl, Mönch, and Fowler (2020)
			Iterated Greedy	Fidelis and Arroyo (2017)
			Simulated Annealing	Yugma et al. (2012), Knopp, Dauzere-Peres, and Yugma (2014), Knopp, Dauzère-Pérès, and Yugma (2017), Fidelis and Arroyo (2017), Vimala Rani and Mathirajan (2020a)
			Tabu Search	Vimala Rani and Mathirajan (2020a)
		Population based	Genetic Algorithm	Kim and Kim (2002), Mönch et al. (2002), Balasubramanian et al. (2004), Mönch et al. (2005), Dirk and Monch (2006), Malve and Uzsoy (2007), Dauzère-Pérès and Mönch (2013), Jia, Jiang, and Li (2013b), Lausch and Mönch (2016), Monch and Roob (2018), Rocholl, Mönch, and Fowler (2020), Wu et al. (2021)
			Differential Evolution	Fu, Sivakumar, and Li (2012)
			Memetic Algorithm	Cheng, Chiang, and Fu (2008), Chiang, Cheng, and Fu (2010)
			Ant Colony Optimisation	Li and Qiao (2008), Kashan and Karimi (2008), Li, Qiao, and Wu (2009), Monch and Almeder (2009), Guo, Jiang, and Hu (2010), Li, Qiao, and Pan (2010), Almeder and Monch (2011), Chen et al. (2013), Jia, Wang, and Leung (2016), Lausch and Mönch (2016)
			Large Neighbourhood Search / Variable Neighbourhood Search	Almeder and Monch (2011), Bilyk, Mönch, and Almeder (2014), Lausch and Mönch (2016)
	Mathematical Programming based Heuristics			Sung and Kim (2003), Jolai (2005), Shiqing Yao, Jiang, and & Li (2012)

- Very few studies focus on D-SDF with a re-entrant situation.
- A maximum number of studies are reported in dynamic scheduling compared to static scheduling. However, except few studies, all are considered only the future arrival of jobs.

In addition to mapping the 72 research articles related to the deterministic scheduling of diffusion furnaces based on the proposed classification schemes, this study also carried out various simple meta-analyses to find general trends across the studies on various parameters related to D-SDF, and the same is discussed in the next section.

4. A simple meta-analysis on deterministic scheduling of diffusion furnaces (D-SDF)

A study about a particular study related to the same subject area, which is overwhelming over the period, is called a meta-analysis. Generally, a meta-analysis provides integrated result on the specific topic, already addressed in the literature. Particularly the meta-analysis is very helpful due to the fact that it's a review designed to summarise information on various parameters of the specific topic, considered for meta-analysis.

Our purpose of meta-analysis, in this paper, is descriptive and inductive in nature and not conductive to statistical methodologies for deductive hypothesis testing. Instead, we perform summary counts on various parameters related to D-SDF to get the trend and pattern results

Table 6. Proposed/implemented simple heuristic algorithm(s) for D-SDF research.

Machine Environment		Nature of Scheduling		References
DF as a single work centre	Single Diffusion Furnace	Static		Mehta and Uzsoy (1998), Perez, Fowler, and Carlyle (2005), Devpura et al. (2000), Dobson and Nambimadom (2001), Kashan and Karimi (2008), Monch and Roob (2018)
		Dynamic	Only FA of jobs	Uzsoy (1995), Kurz and Mason (2008), Li and Qiao (2008), Mathirajan and Vimalarani (2012), Paramitha Mansoer and Koo (2015), Vimala Rani and Mathirajan (2016a, 2020a, 2020b)
			J-RTE along with FA of jobs	Vimala Rani and Mathirajan (2014, 2015,2016c, 2021a)
			R-RTE along with FA of jobs	Vimala Rani and Mathirajan (2015, 2016b, 2016c, 2021a)
	Multiple and Homogenous Diffusion Furnaces	Static		Kim et al. (2001), Monch and Almeder (2009), Almeder and Monch (2011), Lausch and Mönch (2016), Jia, Wang, and Leung (2016), Monch and Roob (2018), Rocholl, Mönch, and Fowler (2020)
		Dynamic	Only FA of jobs	Bar-Noy et al. (2002), Christian Artigues et al. (2006), Mönch, Zimmermann, and Otto (2006), Dirk and Monch (2006), Malve and Uzsoy (2007), Cheng, Chiang, and Fu (2008), Cheng, Chiang, and Fu (2008), Li, Qiao, and Wu (2009), Bar-Noy et al. (2009), Kim, Joo, and Choi (2010), Chiang, Cheng, and Fu (2010), Li, Qiao, and Pan (2010), Bilyk, Mönch, and Almeder (2014), Fidelis and Arroyo (2017), Rocholl, Mönch, and Fowler (2020)
			J-RTE along with FA of jobs	**There is no reported study**
			R-RTE along with FA of jobs	**There is no reported study**
	Multiple and Heterogeneous Diffusion Furnaces	Static		**There is no reported study**
		Dynamic	Only FA of jobs	**There is no reported study**
			J-RTE along with FA of jobs	Vimala Rani and Mathirajan (2021a, 2021b)
			R-RTE along with FA of jobs	Vimala Rani and Mathirajan (2021a, 2021b)
Diffusion furnaces along with upstream and/or downstream machine		Static		Su (2003), Yugma et al. (2008), Tanju Yurtsever, Kutanoglu, and Johns (2009), Fu, Sivakumar, and Li (2012), Knopp, Dauzere-Peres, and Yugma (2014), Pirovano et al. (2020)
		Dynamic	Only FA of jobs	Ahmadi et al. (1992), Neale and Duenyas (2000), Sung, Kim, and Yoon (2000), Yugma et al. (2012)
			J-RTE along with FA of jobs	**There is no reported study**
			R-RTE along with FA of jobs	**There is no reported study**
Diffusion furnaces along with re-entrant situation		Static		**There is no reported study**
		Dynamic	Only FA of jobs	Mason, Fowler, and Matthew (2002), Jia, Jiang, and Li (2013a, 2013b), Knopp, Dauzère-Pérès, and Yugma (2017)
			J-RTE along with FA of jobs	**There is no reported study**
			R-RTE along with FA of jobs	**There is no reported study**

in order to shed a greater understanding of the development and evolution of D-SDF and to identify potential research areas for further research and improvement.

In the following sections, we present various simple meta-analyses carried out on the published research related to D-SDF w.r.t. (i) the proposed classification schemes, (ii) data source, maximum size (maximum number of jobs) in the instances, and benchmark procedure considered, (iii) number of articles published, number of contributed authors over the years, top researchers in terms of number of publications, and highly cited research articles, and (iv) publication outlets and publishers.

4.1. A meta-analysis based on the proposed classification schemes (1, 1a, 2, and 3)

Considering the classification scheme 1 (that is, Figure 1), this study computes summary counts and percentages for each of the 12 different combinations of research, and the same is presented in Table 7. This table is expected to provide a deeper understanding of the development/evolution of D-SDF research. Accordingly, from Table 7, the following main inferences are observed:

- D-SDF studies considering DF as a single work centre are carried out much more than considering diffusion furnaces along with upstream and/or downstream machine (74% Vs 19%) and considering diffusion furnaces along with re-entrant situation (74% Vs 7%).

- Dynamic scheduling research is slightly higher than static scheduling research (65% Vs. 35%)

Further, this study carried out the meta-analysis for each of the 15 [= 3 + 3+3 + 3+3] different combinations of research, which are resulted based on *classification scheme 1(a), that is* Figure 2. The results obtained based on this specific meta-analysis is presented in Table 8. From Table 8, it is observed that

- scheduling multiple and homogeneous diffusion furnaces research is higher than scheduling single diffusion furnace (50% Vs. 47%) and scheduling multiple and heterogeneous diffusion furnaces (50% Vs. 3%)
- deterministic scheduling considering DF as a single work center mainly focuses on dynamic scheduling than static scheduling (67% Vs 33%)

Table 7. Distribution of D-SDF research in SM w.r.t. proposed classification scheme 1 (that is, Figure 1).

Machine Environment	Nature of Scheduling		No. of Articles[a]	Percentage of Articles		
Diffusion Furnace as a single work centre	Static		18^{1}	24.31%	**24.3%**	**74%**
	Dynamic	Considering only Future Arrival (FA) of Jobs	30^{1}	40.97%	**49.3%**	
		Considering Job-Related Real-Time Event (J-RTE) along with FA of jobs	5^{4}	4.17%		
		Considering Resource-Related Real-Time Event (R-RTE) along with FA of jobs	5^{4}	4.17%		
Diffusion furnaces along with upstream and/or downstream machine	Static		8	11.11%	**11.1%**	**19%**
	Dynamic	Considering only FA of Jobs	6	8.33%	**8.3%**	
		Considering J-RTE along with FA of jobs	Nil	Nil		
		Considering R-RTE along with FA of jobs	Nil	Nil		
Diffusion furnaces along with re-entrant situation	Static		Nil	Nil	**0**	**7%**
	Dynamic	Considering only FA of Jobs	5	6.94%	**6.9%**	
		Considering J-RTE along with FA of jobs	Nil	Nil		
		Considering R-RTE along with FA of jobs	Nil	Nil		

[a]Represents number of common articles. There are five articles out of 72 related to D-SDF research, accounted twice.

Table 8. Distribution of D-SDF as a single work centre w.r.t. proposed classification scheme 1(a) (that is, Figure 2).

Problem Configurations				No. of Articles[a]	Percentage of Articles			
Single Diffusion Furnace	Static			10^{1}	17.92%	**17.9%**		**47%**
	Dynamic by considering future arrival of Jobs (D-FAJ)		Agreeable Release Time and Due-date	6	11.32%	**29.2%**		
			Non-agreeable Release Time and Due-date	10^{1}	17.92%			
Multiple and Homogeneous Diffusion Furnaces	Without Machine Eligibility Restrictions	Static		9^{1+1}	15.09%	**15.1%**	**50%**	**50%**
		D-FAJ	Agreeable Release Time and Due-date	19^{1}	34.91%	**34.9%**		
			Non-agreeable Release Time and Due-date	Nil	0			
	With Machine Eligibility Restrictions	Static		Nil	0	**0**	**0**	
		D-FAJ	Agreeable Release Time and Due-date	Nil	0	**0**		
			Non-agreeable Release Time and Due-date	Nil	0			
Multiple and Heterogeneous Diffusion Furnaces	Without Machine Eligibility Restrictions	Static		Nil	0	**0**	**0**	**3%**
		D-FAJ	Agreeable Release Time and Due-date	Nil	0	**0**		
			Non-agreeable Release Time and Due-date	Nil	0			
	With Machine Eligibility Restrictions	Static		Nil	0	**0**	**3%**	
		D-FAJ	Agreeable Release Time and Due-date	Nil	0	**2.8%**		
			Non-agreeable Release Time and Due-date	2^{1}	2.83%			

[a]Represents number of common articles. There are three articles out of 53 related to D-SDF as a single work centre research accounted twice.

Table 9. Distribution of D-SDF research in SM w.r.t. the proposed classification scheme 2 (that is, Figure 3).

Scheduling Objectives		No. of Articles	Percentage of Articles	
Completion Time based	**Cmax (Maximum completion time)**	**11**	**9.02%**	**39%**
	TCT (Total completion time)	6	4.92%	
	ACT (Average completion time)	1	0.82%	
	TWCT (Total weighted completion time)	6	4.92%	
	AFT (Average flow time)	2	1.64%	
	CyT (Cycle time)	1	0.82%	
	WCyT (Weighted cycle time)	2	1.64%	
	Waiting time / X-factor	3	2.46%	
	ANJ (Average no. of jobs)	1	0.82%	
	No. of moves	4	3.28%	
	Batch size/ Batching coefficient	3	2.46%	
	Utilisation	1	0.82%	
	Violations of time window constraints / Number of re-cleaned lots / Machine saturation / Avoid scrapped lots	3	2.46%	
	Cost of completing jobs / Electricity power cost / Electricity cost	3	2.46%	
Due-date based	TT (Total tardiness)	6	4.92%	**61%**
	AT (Average tardiness)	1	0.82%	
	TWT (Total weighted tardiness)	**38**	**31.15%**	
	TEL (Total earliness lateness)	4	3.28%	
	TWEL (Total weighted earliness lateness)	1	0.82%	
	Tmax (Maximum tardiness)/ Lmax (Maximum lateness)	10	8.20%	
	NT (No. of tardy jobs)	5	4.10%	
	Weighted no. of tardy jobs	3	2.46%	
	On time	1	0.82%	
	Weight of on time jobs	2	1.64%	
	OTD rate	4	3.28%	

- deterministic and dynamic scheduling considering DF as a single work center mainly focuses on agreeable release time and due-date requirement than non-agreeable release time and due-date requirement (79% Vs. 21%)

In addition to the above, this study computes summary counts and percentages for each of the 25 scheduling objectives in the proposed *classification scheme 2* (that is, Figure 3), to provide a deeper understanding of the growth of D-SDF research w.r.t. the scheduling objectives, and the same is presented in Table 9. From Table 9, the following inferences are observed:

- D-SDF research deals with due date based scheduling objectives (that is, the customer perspective objective) is higher than completion time-based scheduling objectives (that is, the organisation perspective objective) (61% Vs. 39%).
- TWT is the most widely addressed objective among the due-date based scheduling objective (51%).
- Further, among various completion time-based scheduling objectives, Cmax is widely addressed by the researchers (23%), which is the proxy measure for utilisation.

In addition to the above, a summary count and percentage scores computed for each of the 14 combinations, as per the *classification scheme 3* (that is, Figure 4), are presented in Table 10. From Table 10, the following inferences are observed:

- Heuristics are more widely used in D-SDF research than Mathematical programming (68% Vs. 32%) approaches
- In the mathematical programming approaches, many researchers proposed integer linear programming

Table 10. Distribution of D-SDF research in SM w.r.t. proposed classification scheme 3 (that is, Figure 4).

Solution Methodology				No. of Articles	Percentage of Articles		
Mathematical Programming	Integer Linear Programming			26	18.71%	**31.7%**	**32%**
	Dynamic Programming			5	3.60%		
	Theorem & Proof			13	9.35%		
Heuristics	Simple Heuristics			54	38.85%	**38.9%**	**68%**
	Metaheuristics	Single Solution based	Local Search	3	2.16%	**27.3%**	
			Iterated Greedy	1	0.72%		
			Simulated Annealing	5	3.60%		
			Tabu Search	1	0.72%		
		Population based	Genetic Algorithm	12	8.63%		
			Differential Evolution	1	0.72%		
			Memetic Algorithm	2	1.44%		
			Ant Colony Optimisation	10	7.19%		
			large neighbourhood search / Variable neighbourhood search	3	2.16%		
	Mathematical Programming based Heuristics			3	2.16%	**2.2%**	

model than dynamic programming (59% Vs. 11%) model and theorem & proof (59% Vs. 30%).

- Simple heuristic algorithms are most widely used in D-SDF research than meta-heuristics (57% Vs. 40%) and mathematical programming based heuristics (57% Vs. 3%).
- Within meta-heuristics, population-based meta-heuristics are more widely used than single-solution based meta-heuristics (74% Vs.26%). Further, simulated annealing (13%) and Genetic algorithm (32%) are the most widely used algorithms in single-solution based and population-based meta-heuristics respectively.

4.2. A meta-analysis based on the data source, maximum size (maximum number of jobs) in the instances, and benchmark procedure considered

This study computes the percentage of published research papers on D-SDF, which are (a) generating large number of problem instances (that is, more than 100 problem instances) by proposing an experimental design, (b) generating small number of problem instances (that is, less than 100 problem instances) by proposing an experimental design, (c) using the real data, (d) generating random data using a real fab system, and (e) using the data available in the published literature, and presented the same in Table 11. Further, by analyzing each of the D-SDF research articles, this study understood that some of the research articles considered the maximum number of jobs in their instance to be as same as the existing literature considered and others considered the new maximum size. Accordingly, there are 27 different maximum sizes are considered as the maximum number of jobs in the entire D-SDF research articles. This study computes the percentage of D-SDF research articles, which are considered the each of these 27 maximum sizes (that is, the maximum number of jobs) considered in their study, and the same is presented in Table 11. In addition to that, this study computes the percentage of articles, which are carried out the performance analysis in comparison with benchmark procedures such as exact approach/estimated optimal procedure/lower bound procedure/obtained best solution/earlier best known method in the literature/one of the proposed method/previous method in practice, and presented the same in Table 11. From Table 11, this study observed the following.

- Most of the studies used the large number of problem instances generated by proposed experimental design than (i) small number of problem instances generated by proposed experimental design (70% Vs 11%), (ii) real data (70% Vs 13%), (iii) randomly generated data from the real fab system (70% Vs 5%), and (iv) the data available in the published literature (70% Vs 2%).
- 24.1% of the D-SDF research articles (i.e. 14 research articles) considered the maximum size (maximum number of jobs) in the instances as 100 jobs, and 13.8% of the research articles (i.e. 8 research articles) considered 300 jobs.
- 5.2% of research articles (i.e. 3 research articles) each considered the maximum size in the problem instances as 360 jobs, 400 jobs, 500 jobs, and 3600 jobs respectively,
- 3.5% of research articles (i.e. 2 research articles) each considered the maximum size in the problem instance as 12 jobs, 60 jobs, and 240 jobs respectively.
- 1.7% of research articles (i.e. one article) each considered the maximum size in the problem instance as 10 jobs, 13 jobs, 18 jobs, 20 jobs, 40 jobs, 50 jobs, 80 jobs, 120 jobs, 150 jobs, 180 jobs, 200 jobs, 346 jobs, 450 jobs, 480 jobs, 600 jobs, 700 jobs, 864 jobs, and 5000 jobs respectively.

Table 11. Distribution of number of articles on D-SDF in percentage w.r.t. to data source, maximum number of jobs in the instances, and benchmark procedure considered.

Distribution of D-SDF research articles w.r.t. to data source considered	
Type	**Percentage of Articles**
Large number of problem instances generated from the proposed experimental design	70%
Small number of problem instances generated from the proposed experimental design	11%
Real data	13%
Randomly generated data from the real fab system	5%
Data from the literature	2%

Distribution of D-SDF research articles w.r.t maximum number of jobs considered in the instances	
Type	**Percentage of Articles**
100 jobs	24.1%
300 jobs	13.8%
360 jobs	5.2%
400 jobs	5.2%
500 jobs	5.2%
3600 jobs	5.2%
12 jobs	3.5%
60 jobs	3.5%
240 jobs	3.5%
10 jobs	1.7%
13 jobs	1.7%
18 jobs	1.7%
20 jobs	1.7%
40 jobs	1.7%
50 jobs	1.7%
80 jobs	1.7%
120 jobs	1.7%
150 jobs	1.7%
180 jobs	1.7%
200 jobs	1.7%
346 jobs	1.7%
450 jobs	1.7%
480 jobs	1.7%
600 jobs	1.7%
700 jobs	1.7%
864 jobs	1.7%
5000 jobs	1.7%

Distribution of D-SDF research articles w.r.t. to benchmark procedure considered	
Type	Percentage of Articles
Exact approach	9%
Estimated optimal procedure	15%
Lower bound procedure	11%
Obtained best solution	11%
Earlier best known method in the literature	45%
One of the proposed methods	5%
Previous method in practice	5%

- More number of D-SDF research articles considered earlier best known method in the literature as the benchmark procedure than considering (i) exact approach (45% Vs 9%), (ii) estimated optimal procedure (45% Vs 15%), (iii) lower bound procedure (45% Vs 11%), (iv) obtained best solution (45% Vs 11%), (v) one of the proposed methods (45% Vs 5%), and (vi) previous method in practise (45% Vs 5%).

4.3. A meta-analysis based on number of articles published, number of contributed authors over the years, top researchers in terms of number of publications, and highly cited papers

To understand the growth of the D-SDF research, this study computes the frequency distribution of D-SDF research articles published in every two years, from 1992 to 2021. Corresponding to each of these frequency distributions, a number of researchers involved in the publications, and the number of distinct researchers involved in the publication are also computed and these statistics are presented in Figure 5

From Figure 5, it is observed that most of the time, the number of researchers contributed and the number of distinct researchers contributed are either the same or very close to each other. This indicates a healthy constant trend in D-SDF research. This study also observed that the number of articles published and the number of researchers contributed in the year 2020–2021 are higher than in 2018–2019. With these backdrops, this study believed that there will be an increasing research trend in D-SDF research in the upcoming years. Further, this study observed that there are 104 distinct researchers involved in publishing 72 D-SDF research articles. In that, 13 D-SDF articles are contributed by the researcher: Monch, and 11 D-SDF articles are contributed by the researcher: Mathirajan and Vimala Rani jointly.

Moreover, this study captures citation scores (as of 9th July 2021) for each of the 72 research articles related to D-SDF research through Google Scholar and identifies the top 20 highly cited D-SDF research articles and the same is given in Table 12 for the benefit of readers/researchers in this area.

4.4. A meta-analysis based on the publication outlets and publishers

The number of D-SDF research articles published in various journals and proceedings during the period 1992 to 2021 is computed and the same is presented in Table 13. It is observed from Table 13 that, out of 72 articles, 25 articles are from various conference proceedings (IEEE, IEEE-IEEM, IEEE-ASMC, OR, WSC), one research article is from lecture notes in computer science, two research article is from International Series in Operations Research & Management Science, and 44 research articles are from 24 different journals. In that, the journals: International Journal of Production Research, and Computers & Operations Research have the highest number of articles. As the number of articles published in some of the journals is very few, the published sources of journals

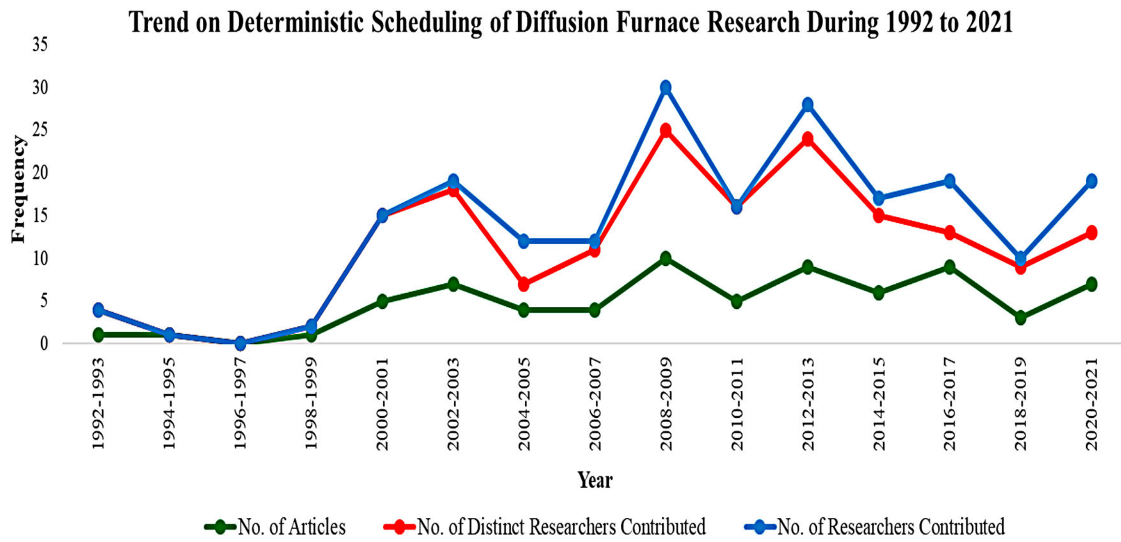

Figure 5. Trend on deterministic scheduling of diffusion furnaces (D-SDF) research.

Table 12. Top 20 Highly Cited D-SDF Research Articles, as of 9th July 2021.

Title of the Article	Reference	Number of Citations
Batching and scheduling jobs on batch and discrete processors	Ahmadi et al. (1992)	299
Scheduling batch processing machine with incompatible job families	Uzsoy (1995)	246
A modified shifting bottleneck heuristic for minimising the total weighted tardiness in complex job shops	Mason, Fowler, and Matthew (2002)	242
Heuristic scheduling of jobs on parallel batch machines with incompatible job families and unequal ready times	Mönch et al. (2005)	233
Minimising total tardiness on a batch processing machine with incompatible job families	Mehta and Uzsoy (1998)	216
The batch loading and scheduling problem	Dobson and Nambimadom (2001)	195
A genetic algorithm for minimising maximum lateness on parallel identical batch processing machines with dynamic job arrivals and incompatible job families	Malve and Uzsoy (2007)	173
Genetic algorithm based scheduling of parallel batch machines with incompatible job families to minimize total weighted tardiness	Balasubramanian et al. (2004)	156
Minimising total weighted tardiness on a single batch process machine with incompatible job families	Perez, Fowler, and Carlyle (2005)	127
A hybrid two-stage flow-shop with limited waiting time constraints	Su (2003)	117
Production scheduling in a semiconductor wafer fabrication facility producing multiple product types with distinct due dates	Kim et al. (2001)	114
A memetic algorithm for minimising total weighted tardiness on parallel batch machines with incompatible job families and dynamic job arrival	Chiang, Cheng, and Fu (2010),	82
Machine learning techniques for scheduling jobs with incompatible families and unequal ready times on parallel batch machines	Mönch, Zimmermann, and Otto (2006)	
A problem reduction and decomposition approach for scheduling for a flow shop of batch processing machines	Sung, Kim, and Yoon (2000)	77
Minimising number of tardy jobs on a batch processing machine with incompatible job families	Jolai (2005)	72
A batching and scheduling algorithm for the diffusion area in semiconductor manufacturing	Yugma et al. (2012)	62
Minimising due date related performance measures on two batch processing machines	Sung and Kim (2003)	50
Multiobjective Scheduling of Jobs with Incompatible Families on Parallel Batch Machines	Dirk and Monch (2006)	49
Scheduling a single batch-processing machine with arbitrary job sizes and incompatible job families: An ant colony framework	Kashan and Karimi (2008)	48
Metaheuristic for scheduling jobs with incompatible families on parallel batching machines	Almeder and Monch (2011),	45
Scheduling jobs with ready times and precedence constraints on parallel batch machines using metaheuristics	Bilyk, Mönch, and Almeder (2014)	
Minimising total weighted tardiness on single batch process machine with incompatible job families	Devpura et al. (2000)	44

are grouped into disciplines wise such as Computer Science (CS), Industrial Engineering (IE), Manufacturing (MANUF), Operations Management (OM), Operations Research (OR), Scheduling (SCH), and Business Economics (BE).

Accordingly, the distribution of articles by journals (discipline-wise) is computed and given in the last column of Table 13. The last column of Table 13 indicates that a greater number of articles had been published in OR (45%) related journals. This clearly indicates the utility of OR in D-SDF research. Further, there is a good number of D-SDF research articles published in OM (18%), IE (14%), MANUF (9%), and CS (9%) related journals. These details would help the researcher to identify their possible publication outlet when they are ready to submit his/her research article.

Table 13. Discipline wise the Distribution of D-SDF Articles' Publication Outlet.

Sl. No	Publication Outlet	Publisher	No. of Articles	Discipline Code	Discipline wise Total & Percentage
1	ACM Transactions on Algorithms	ACM	1	CS	**4 [9%]**
2	Applied Soft Computing	Elsevier	2	CS	
3	Engineering Applications of Artificial Intelligence	Elsevier	1	CS	
4	Computers and Industrial Engineering	Elsevier	2	IE	**6 [14%]**
5	IIE Transactions	Taylor & Francis	2	IE	
6	International Journal of Industrial and Systems Engineering	Inderscience	1	IE	
7	Journal of Industrial and Intelligent Information	Engineering and Technology	1	IE	
8	IEEE Transactions on Robotics and Automation	IEEE	1	MANUF	**4 [9%]**
9	IEEE Transactions on Semiconductor Manufacturing	IEEE	2	MANUF	
10	Journal of Engineering Manufacture	Sage	1	MANUF	
11	International Journal of Operations and Quantitative Management	International Forum of Management Scholars	1	OM	**8 [18%]**
12	International Journal of Production Research	Taylor & Francis	6	OM	
13	Production Planning and Controls	Taylor & Francis	1	OM	
14	Applied Mathematical Modelling	Elsevier	1	OR	**20 [45%]**
15	International Journal of Mathematical, Engineering, and Management Sciences	IJMEMS	1	OR	
16	Computers and Operations Research	Elsevier	6	OR	
17	European Journal of Operational Research	Elsevier	5	OR	
18	International Journal of Operational Research	Inderscience	1	OR	
19	Journal of Information & Optimisation Sciences	Taylor & Francis	1	OR	
20	Journal of the Operational Research Society	Taylor & Francis	2	OR	
21	Operations Research	INFORMS	2	OR	
22	OPSEARCH	Springer	1	OR	
23	Journal of Scheduling	Springer	1	SCH	**1 [2%]**
24	Journal of Business Economic	Springer	1	BE	**1 [2%]**
1	Lecture Notes in Computer Science		1	CS	
2	International Series in Operations Research & Management Science		2	OR	
3	Conference Proceedings: IEEE, IEEE-IEEM, IEEE-ASMC, OR, WSC, Others		25	Proc	

CS: Computer Science; IE: Industrial Engineering; MANUF: Manufacturing; OM: Operations Management; OR: Operations Research; SCH: Scheduling; ACM: Association for Computing Machinery; BE: Business Economics; INFORMS: Institute for Operations Research and the Management Sciences.

This study also analyses the publisher of 24 different journals, which had published D-SDF research articles and observed that Elsevier published a greater number of D-SDF research articles than Taylor & Francis [39% Vs 27%], IEEE [39% Vs 7%], Springer [39% Vs 7%], Inderscience [39% Vs 5%], INFORMS – Institute for Operations Research and the Management Sciences [39% Vs 5%], Association for Computing Machinery (ACM) [39% Vs 2%], Engineering and Technology [39% Vs 2%], International Forum of Management Scholars [39% Vs 2%], IJMEMS [39% Vs 2%], and Sage [39% Vs 2%]. These details would help the researcher to identify their possible publisher when they are ready to submit his/her research article.

5. Summary and conclusion

Since widespread research articles are available on the deterministic scheduling of diffusion furnaces (D-SDF) in the semiconductor manufacturing industry and there is no study on the review of literature, this study attempts to present a systematic literature review of all existing literature on D-SDF along with a meta-analysis. Accordingly, a detailed literature review has been carried out on D-SDF research from various journals, conference proceedings, lecture notes in computer science, etc., and identified 72 research articles published during the period 1992 to 2021. All these 72 articles are thoroughly analysed to understand the problem configuration considered, solution methodologies proposed, objective(s) considered, data source involved, maximum size (maximum number of jobs) in the instances, and benchmark procedure considered. Accordingly, multiple classification schemes are proposed and mapped the 72 articles as per the proposed classification schemes. The mapping of all these 72 research articles in the proposed classification schemes has provided the following important information for the researchers who are interested to conduct research in the area of D-SDF:

- New research problems w.r.t. to problem configuration/scheduling objective/solution methodology can be derived.
- References of closely related existing research studies w.r.t. any researcher's problem on D-SDF can be

obtained and this will ease the researcher's literature review process.

Further, considering the proposed classifications schemes and various parameters w.r.t. to the published research papers on D-SDF, this study carried out various simple meta-analyses in the form of summary counts and percentages and observed that most of the studies considered

- dynamic situation rather than the static situation,
- DF as a single work center rather than considering DF along with upstream/downstream operation and/or re-entrant situation,
- customer perspective objectives (that is due date based scheduling objective),
- simple heuristic rather than other solution methodologies,
- large number of problem instances generated from the proposed experimental design,
- the maximum size (maximum number of jobs) in the instances as 100,
- earlier best known method in the literature as the benchmark procedure.

In addition to the above, the following are also observed from the meta-analyses:

- There will be an increasing research trend in D-SDF research in the upcoming years since the number of articles published and the number of researchers contributed in the year 2020–2021 is higher than in 2018–2019. Further, most of the time, the number of researchers contributed and the number of distinct researchers contributed are either the same or very close to each other.
- Among 24 different journals which have D-SDF research articles, International Journal of Production Research, and Computers & Operations Research have the highest number of D-SDF research articles.
- A greater number of D-SDF research articles had been published in operation research (OR) related journals.
- Elsevier published a greater number of D-SDF research articles and followed by Taylor & Francis.
- Ahmadi et al. (1992) have a greater number of citations in D-SDF research articles.
- Researchers: Monch, Mathirajan, and Vimala Rani have contributed more number papers in D-SDF research.

We acknowledge that this review cannot be claimed to be exhaustive (for example – this study didn't discuss the quality of the developed methods, main results of the reviewed D-SDF research articles), but it does provide reasonable insights into the state-of-the-art on D-SDF research in the semiconductor manufacturing industry. Thus, it is hoped that this review will provide a source of reference for other researchers/readers interested in D-SDF research, and help stimulate further interest. The contribution of this study is to propose the classification schemes and conduct various meta-analyses for analysing 72 identified research articles to suggest *and/or* bring to light some unexplored research problems, and to know the current research trends & future research directions on D-SDF research.

Future work will concentrate on the development of a web-based repository for D-SDF research (i) for obtaining all the results of the classifications schemes and all the meta-analyses carried out in this study in a mouse-click, and (ii) to quickly get all the required closely related bibliography in a various reference standard.

Data availability statement

The data that support the findings of this study are available from the corresponding author, [M Vimala Rani] on the request.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Annexure 1: A sample summary of 10 research articles on D-SDF.

		Problem configuration																
		Machine environment							Job characteristics									
			MDF-SWC						Job family			Job arrival					Release time & due-date	
S. No	Reference	SDF-SWC	Homogeneous DF	Heterogeneous DF	With machine eligibility	Without machine eligibility	DF-U/D	DF-R	Single	Multiple compatible	Multiple in-compatible	S	D-FA	D-JRTE	D-RRTE	Due-date considered (Yes/No)	Agreeable	Non agreeable
1	Ahmadi et al. (1992)						X				X		X			No	NA	
2	Uzsoy (1995)	X									X		X			Yes	X	
3	Mehta and Uzsoy (1998)	X									X	X				Yes	NA	
4	Neale and Duenyas (2000)						X		X				X			No	NA	
5	Devpura et al. (2000)	X									X	X				Yes	NA	
6	Sung, Kim, and Yoon (2000)						X		X				X			No	NA	
7	Dobson and Nambimadom (2001)	X									X	X				No	NA	
8	Kim et al. (2001)		X			X					X	X				Yes	NA	
9	Kim and Kim (2002)						X		X			X				No	NA	
10	Mönch et al. (2002)		X			X					X	X				Yes	NA	

SDF-SWC: Single DF as single work centre MDF-SWC: Multiple DF as single work centre DF-U/D: DF along with upstream/downstream machine DF-R: DF along with re-entrant situation S: Static. D-FA: Dynamic considering future arrival of jobs D-JRTE: Dynamic considering job related RTE along with FA of jobs D-RRTE: Dynamic considering resource related RTE along with FA of jobs.

(Annexure 1: A sample summary of 10 research articles on D-SDF- contd ...)

		Solution methodologies							Objective				
									No. of objective				
				MH based on						MO		Based on	
S. No	Reference	MP	SH	SS	Population	MPBH	Data source with number of problem instances and maximum size [Maximum number of jobs (MNJ)] considered in the instances	Benchmark method	SO	Optimise one at a time as SO	Optimise simultaneously	Completion time	Due-date
1	Ahmadi et al. (1992)		X				Small number of problem instances (45 instances) generated from the proposed experimental design; MNJ:400	Lower bound		X		Cmax, TCT	
2	Uzsoy (1995)		X				Large number of problem instances (2640 instances) generated from the proposed experimental design; MNJ:150	Obtained best solution		X		Cmax, TWCT	Lmax
3	Mehta and Uzsoy (1998)	DP,TP	X				Large number of problem instances (1280 instances) generated from the proposed experimental design; MNJ:360	Optimal Solution	X				TT
4	Neale and Duenyas (2000)	DP	X				Small number of problem instances (32 instances) generated from the proposed experimental design; MNJ:18	Lower bound		X		ANJ, TCT	
5	Devpura et al. (2000)		X				Large number of problem instances (320 instances) generated from the proposed experimental design; MNJ:180	Earlier best method in the literature	X				TWT
6	Sung, Kim, and Yoon (2000)	TP	X				Large number of problem instances (640 instances) generated from the proposed experimental design; MNJ:500	Lower bound		X		Cmax, TCT	
7	Dobson and Nambimadom (2001)	ILP,TP	X				Large number of problem instances (240 instances) generated from the proposed experimental design; MNJ: 500	Optimal Solution/Lower bound	X			AFT	
8	Kim et al. (2001)		X				Randomly generated data using real fab; MNJ:50	Earlier best method in the literature	X				TT
9	Kim and Kim (2002)				GA		Small number of problem instances (50 instances) generated from the proposed experimental design; MNJ:400	Earlier best method in the literature	X			TCT	
10	Mönch et al. (2002)				GA		Large number of problem instances (960 instances) generated from the proposed experimental design; MNJ:300	Earlier best method in the literature	X				TWT

MP: Mathematical Programming SH: Simple heuristics MH: Metaheuristics SS: Single solution MPBH: Mathematical programming based heuristic TP: Theorem & Proof DP: Dynamic Programming. ILP: Integer linear programming SO: Single objective MO: Multi objective.

Annexure 2: Sample review of D-SDF research article related to 1st row and 10th row in Annexure 1

The study by Ahmadi et al. (1992) focused on deterministic scheduling of diffusion furnaces along with upstream and/or downstream operation, multiple incompatible job families, and dynamic job arrival. They proposed a simple heuristic to optimise Cmax and TCT one at a time as a single objective. Further, they generate small number of problem instances [45 instances, and maximum size (maximum number of jobs) in the instances is 400] by the proposed experimental design and carried out the performance evaluation in comparison with lower bound

Mönch et al. (2002) focused on the deterministic scheduling of multiple homogeneous diffusion furnaces with multiple incompatible job families in a static situation. They have implemented genetic algorithm to minimize TWT. Further, this study carried out the performance evaluation in comparison with an earlier best method in the literature considering large number of problem instances [960 instances, and the maximum size (maximum number of jobs) in the instances is 300], generated by the proposed experimental design.

Annexure 3: D-SDF research articles which are optimising more than one objective simultaneously

References	Multi objectives
Dirk and Monch (2006), Li, Qiao, and Pan (2010), Chen et al. (2013)	Cmax and TWT
Christian Artigues et al. (2006), Yugma et al. (2008), Yugma et al. (2012)	Number of Moves, Batching Coefficient, & X-factor
Jung et al. (2013), Jung et al. (2014)	WCyT/Min Violations of the time window constraint
Vimala Rani and Mathirajan (2016c)	TWT, NT, OTD rate, TEL, and Lmax
Pirovano et al. (2020)	AFT, Number of re-cleaned lots, Machine saturation, and Avoid scrapped lots
Rocholl, Monch, and Fowler (2018)	TWCT, and Electricity power cost
Rocholl, Mönch, and Fowler (2020)	TWT, and Electricity cost