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Invited Review

Flexibility in manufacturing system design: A review of recent approaches from Operations Research

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Due to increasing demand uncertainty and product variety, manufacturing systems must continually adapt to maintain productivity. Generally, decision-makers can maintain flexibility to account for these adaptations efficiently already in the design phase of manufacturing systems. Consequently, over the past few decades, a significant body of literature has addressed manufacturing system design associated with various manufacturing paradigms, claiming to provide the 'right' level of flexibility. Advanced analytical methods from Operations Research are frequently used in this domain to support decision-making. However, articles on the manufacturing paradigms remain in disjunct literature streams. In this article, we review literature from the last two decades that focuses on the application of Operations Research methods in manufacturing system design. The analyzed articles were selected from peer-reviewed scientific literature in a systematic search and screening process. To unite literature on different manufacturing paradigms, the concept of manufacturing flexibility is adapted, focusing on flexibility types required and considered in manufacturing systems' design phases. The reviewed articles frequently employ mixed-integer linear programming or propose heuristic procedures. Most contributions evaluate static and deterministic settings, overlooking short- or long-term uncertainties in the design of manufacturing systems. Predominantly, flexibility is maintained to enhance economic or performance-oriented objectives. The consideration of social or ecological indicators, however, is barely found. Therefore, research perspectives from this analysis include integrating social and ecological indicators into multi-objective decision-making methods, anticipating neighboring planning problems during design, and applying systematic procedures to address uncertainty.

1. Introduction

Adam Smith emphasized the advantages of the division of labor on the famous 'pin example' in 1776. In this example, he observed a substantial increase in productivity resulting from the specialization of workers (Smith, 1776/1979). In the 20th century, Henry Ford introduced assembly lines for complex products motivated by the use of conveyors in meat-processing plants in Chicago. Therefore, he complemented the specialization of workers by linking the material flow between them, accounting for a further increase in the manufacturing efficiency of standardized goods (Ford, 1923/2015). With the advent of industrial robots, further efficiency gains in manufacturing resulted from the increasing levels of automation in subsequent decades, which are particularly popular in environments with high and steady product demand (Kuhn, 1998; Müller, 2019).

In the later decades of the 20th century, the industrial paradigm of economies of scale was expanded toward economies of scope as the differentiation of products became increasingly important and is widely spread in manufacturing corporations nowadays. The mass customization of products refers to corporations' ability to provide customized products in high volumes at reasonable costs (Davis, 1989). The increasing demand for individualized products (Åhlström & Westbrook, 1999) was accompanied by shorter product life cycles and expanding competition among industrial actors (Pine, 1993). Consequently, manufacturing companies must maintain a high degree of flexibility in their processes to account for the required product variety (Da Silveira, Borenstein & Fogliatto, 2001). The necessary planning of industrial production processes is usually decomposed. Frequently, this is based on the stages of the value chain (procurement, production, distribution, and sales)

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Table 1
Reviews on FMS, CMS, and RMS design using Operations Research approaches.

Author(s)	Year	Stream	Objective
Buzacott and Yao	1986	FMS	Review of analytical models for the design of FMS
Kusiak	1986	FMS	Review of analytical models for the design of FMS
Tempelmeier and Kuhn	1993	FMS	Review of planning problems for the design of FMS
Papaioannou and Wilson	2010	CMS	Review of cell formation problems focusing on formulations and solution approaches
Askin	2013	CMS	Review of the development of design approaches of CMS
Renzi et al.	2014	RMS	Review of the design of cellular RMS focusing on optimization approaches
Bortolini, Galizia and Mora	2018	RMS	Review of RMS, highlighting the application areas, key methodologies, and tools
Yelles-Chaouche et al.	2020	RMS	Review of articles related to RMS planning problems and their solution methods

and the planning horizon (long-term, mid-term, short-term) they are associated with (Fleischmann, Meyr & Wagner, 2015; Rohde, Meyr & Wagner, 2000; Schneeweiss, 2003; Stadtler, 2005). The high product variety fundamentally changes the required processes in the production stage mainly due to the corporations' increased exposure to demand variability regarding the total demand per period and its composition. A major challenge is therefore related to determining the 'right' levels of flexibility and efficiency of the manufacturing processes associated with the offered product portfolio (Volling et al., 2013).

The manufacturing processes are executed using manufacturing systems. A manufacturing system combines humans, machinery, and stations connected by a common material and information flow. In the *design of manufacturing systems*, a mapping of performance requirements expressed by specific performance indicators (e.g., cost, quality, flexibility, time) onto suitable values of decision variables that describe the physical design or the manner of operation of the manufacturing system is addressed. In academic literature, the overall manufacturing system design is decomposed into subproblems of manageable complexity (Chryssolouris, 1992). To this end, decisions on an appropriate quantity of individual resources (which we relate to as a collective term of human workers, machinery, and stations) are required (*capacity decisions*). Evaluating tradeoffs between resources of different flexibility gained attention in this field (Ahmed & Sahinidis, 2008; Gaimon & Singhal, 1992). Subsequently, the resources must be located on the shop floor (*layout decisions*). In these, decisions on the type of material handling system and the connection of resources are important (Asef-Vaziri & Laporte, 2005). Further, the remaining flexibility maintained in the system must be specified for its particular assembly (*configuration decisions*) (Bi et al., 2008). These relate to the resources (e.g., the selection of machine modes or the training of workers) or the material handling system (e.g., bundling of resources to a common material flow). Additionally, one may find it beneficial to anticipate superordinate or subordinate decisions. These address the allocation of aggregate forecasted product demand to multiple manufacturing sites of a corporation (*production planning decisions*) (Melo, Nickel & Saldanha-da-Gama, 2009), or the short-term execution of the production processes (*control decisions*) (Hendry & Kingsman, 1989).

In the past decades, several literature streams have been associated with the development of design approaches for manufacturing systems for different *manufacturing paradigms* aiming to provide a balance of efficiency and flexibility, the most renowned of which are flexible manufacturing systems (FMS), cellular manufacturing systems (CMS), and reconfigurable manufacturing systems (RMS). However, these literature streams individually refer to the characteristics they originally introduced and maintain different terminology. The lack of a uniform consideration of these approaches is also reflected by the overview of related literature reviews, which are mainly divided according to the literature streams (cf. Table 1). Therefore, it is not trivial to distinguish the different types of flexibility the approaches maintain. A classification scheme to classify design approaches for manufacturing systems is urgently needed to unite approaches of the FMS, CMS, and RMS literature streams and provide a common basis for considering flexibility in manufacturing system design. As the focus is on individual manufacturing systems, articles on flexibility in supply chains are not contained within scope (Erengüç, Simpson & Vakharia, 1999; Ivanov, Das & Choi, 2018; Stevenson & Spring, 2007; Yusuf et al., 2004).

As decision-making in the design of manufacturing systems considers a variety of design decisions and various aspects relevant to practice may restrict the decision makers' possibilities for actions, a highly complex domain is faced necessitating the application of advanced analytical methods. Therefore, the objective of this paper is to review the use of Operations Research methods to facilitate the design of manufacturing systems with a focus on the considered flexibility types and their attributes. The review is based on 144 articles from the scientific literature selected in a systematic search and screening process. The analysis aims at highlighting the boundaries of knowledge and identifying potential research gaps.

The main contributions of this review are threefold. First, it provides a unification of previously disjunct literature streams focusing on flexibility in manufacturing system design. To provide a classification scheme of flexibility types consistent across the literature streams, the conceptual framework of 'manufacturing flexibility' is adapted. Second, the related methods are classified and the extent to which recent approaches from Operations Research support manufacturing system design is evaluated. Third, this article identifies blank spots based on the previously described analyses to guide future research from practical and methodical perspectives.

The remainder of this paper is structured as follows. Section 2 outlines the major developments of flexibility in manufacturing system design to facilitate the readers' understanding of the advent of the manufacturing paradigms. In Section 3, the method of the literature review is described. Aggregate descriptive analyses of the review database and insights into the considered problem setting of the articles are presented in Section 4. Section 5 provides an overview of the framework of manufacturing flexibility, which serves as a basis to unite the associated literature streams. Subsequently, the articles in the review database are classified according to the flexibility types and their attributes they address, the developed methods are analyzed, and emerging topics for future research are derived. The article closes with conclusions in Section 6.

2. Major developments of flexibility in manufacturing system design

In the 1970s, manufacturing companies were increasingly confronted with shortened product life cycles, product mix and demand fluctuations, and a rapid change in process technology. At that time, the prevailing manufacturing paradigms focused on flexibility or efficiency. On the one hand, dedicated manufacturing systems specialized in producing low-variant products efficiently exploiting economies of scale; however, their specialization inhibited high flexibility (Gupta & Goyal, 1989b; Koren et al., 1999). On the other hand, job shops were used to provide various products flexibly; however, the increasing product mix resulted in a further decline in the efficiency of job shops (Greene & Sadowski, 1984).

To increase efficiency and flexibility in manufacturing systems, the manufacturing paradigm of cellular manufacturing systems was created based on the concept of *group technology* by Burbidge (1975). Generally, group technology refers to classifying, grouping, and uniting similar concepts, operations, or technologies to exploit their proximity concerning predefined attributes (Greene & Sadowski, 1984; Singh, 1993). In CMS, group technology is utilized to physically divide the resources of a manufacturing system into separate cells (cell formation) and logically divide products into product families based on their similarity regarding design and required manufacturing operations (product family grouping). Each product family is subsequently assigned to one manufacturing cell. By grouping complementary resources for the product family production, intercellular material handling is reduced, the control of operations is enhanced, and setup times and work-in-process inventory are reduced (Greene & Sadowski, 1984; Offodile, Mehrez & Grznar, 1994; Singh, 1993; Stnha & Hollier, 1984). Unlike dedicated manufacturing systems, CMS offer increased possibilities to exploit the flexibility of the manufacturing system's components. Consequently, significant research was conducted to derive beneficial designs based on the CMS paradigm. For a comprehensive overview of early Operations Research methods supporting the design of CMS, please refer to Singh (1993) and Offodile, Mehrez and Grznar (1994).

At the same time, motivated by the advances in computer and numerical control techniques, independent research groups came up with other means to overcome the lack of flexibility in dedicated manufacturing systems (Buzacott & Yao, 1986). Williamson (1968) and Wynne and Hutchinson (1974) investigated the limitations of dedicated manufacturing systems and job shops and proposed numerical control to extend communication and control in manufacturing systems. Consequently, they advanced the development of the manufacturing paradigm of flexible manufacturing systems. FMS consist of integrated, computer-controlled complexes of automated material handling devices and machine tools to process a variety of product types simultaneously. To enable the processing of different product types, the machines are equipped with tool magazines that allow for automated tool changes without significant setup time and are operated in standardized stations. Thus, FMS reduce labor costs and lead times compared to job shops by incorporating a high degree of automation while maintaining the efficiency of dedicated manufacturing systems (Browne et al., 1984; Tempelmeier & Kuhn, 1993).

The manufacturing paradigm of flexible manufacturing systems was developed to serve the production of medium-sized volumes of a variety of products. Changes in demand and product variants are anticipated a priori in the design phase of FMS by implementing all required numerically controlled machines and tools. The components are tightly linked together, limiting the capabilities of later changes in terms of functionality or capacity (Mehrabi et al., 2002). Thus, the paradigm of FMS maintains *generalized flexibility* (ElMaraghy, 2005; Mehrabi, Ulsoy & Koren, 2000; Mehrabi et al., 2002). The generalized flexibility is often not fully utilized as the systems are designed only once based on forecasts and not adjusted after that. Given the high initial investment for these systems and the lack of adjustment possibility, flexibility and efficiency objectives must be carefully balanced against one another (ElMaraghy, 2005; Gupta & Goyal, 1989b). Consequently, significant research was conducted to determine the 'right' levels of flexibility and efficiency in designing FMS. For a comprehensive overview of early Operations Research methods supporting the design of FMS, please refer to Kusiak (1986), Buzacott and Yao (1986), and Tempelmeier and Kuhn (1993).

In the 1990s, computer-aided design dramatically reduced product development times, leading to shorter product life cycles, dynamic product demand, and increased product customization possibilities. Although providing generalized flexibility, the limited capabilities of upgrading or reconfiguring FMS imposed severe limitations to following market changes efficiently. Consequently, a novel manufacturing paradigm was desired (Bortolini, Galizia & Mora, 2018; Koren et al., 1999). In this context, Koren et al. (1999) introduced reconfigurable manufacturing systems. RMS can be defined as manufacturing systems that offer the possibility to add, remove, interchange, or modify manufacturing components (i.e., reconfigurable machines, workers, stations, or material handling units) to respond to changing external developments (ElMaraghy, 2005; Koren et al., 1999). Unlike the integral architecture of FMS, which complicates the identification and separation of the manufacturing system's components, RMS propose an architecture that facilitates the change of single components, mainly by relying on modular machine tools and open software architecture systems (Koren et al., 1999; Matta, Tolio & Tontini, 2004; Mehrabi et al., 2002). Therefore, RMS aim to overcome the limited adjustment possibilities of FMS by providing an architecture that allows the frequent reconfiguration of the manufacturing system to better cope with changing external developments (Koren et al., 1999). Instead of providing a great extent of generalized flexibility during the design phase, RMS provide *customized flexibility* through reconfiguring the manufacturing system to adapt the 'right' level of flexibility when needed (ElMaraghy, 2005). This development extended the research focus of determining the 'right' levels of flexibility of the initial design to the reconfiguration of manufacturing systems allowing consideration of flexibility over time. For a comprehensive overview of Operations Research methods supporting the design of RMS, please refer to Bortolini, Galizia and Mora (2018) or Yelles-Chaouche et al. (2020).

In the 2010s, manufacturing systems kept evolving towards a higher degree of automation. Under the collective terms of *Industry 4.0* or *smart manufacturing*, several new technologies arose that integrated the components of manufacturing systems with sensors, advanced computing platforms, and communication technology (Kusiak, 2018). The technological developments aim to integrate a higher level of automation into manufacturing processes to achieve high efficiency by connecting the physical manufacturing system and its components to virtual technologies, consequently forming Cyber-Physical Systems (Alcácer & Cruz-Machado, 2019). Using those technologies is promoted to offer potential cost reductions of 10–20% in both manufacturing and logistics (Bauernhansl, 2017). If this appraisal proves correct, new potentials to enhance the flexibility and efficiency of production can be leveraged. Additionally, new manufacturing techniques, e.g., additive manufacturing or collaborative robots, offer alternatives to the currently used resources. In this domain, the simultaneous application and interaction of different technologies may facilitate synergies in increasing the technology's performance to a level higher than with their individual use (Flynn et al., 2016; Lauwers et al., 2014; Zhu et al., 2013). Depending on the characteristics of the technologies under consideration, additional optimization problems can arise within the manufacturing system design problems. This is evident, for instance, in the use of collaborative robots in assembly, where multi-mode resource constrained scheduling problems intertwine with the original problem (Sikora & Weckenborg, 2023; Weckenborg et al., 2020). Due to the increasing complexity of industrial manufacturing systems and the growing portfolio of available technologies and data,

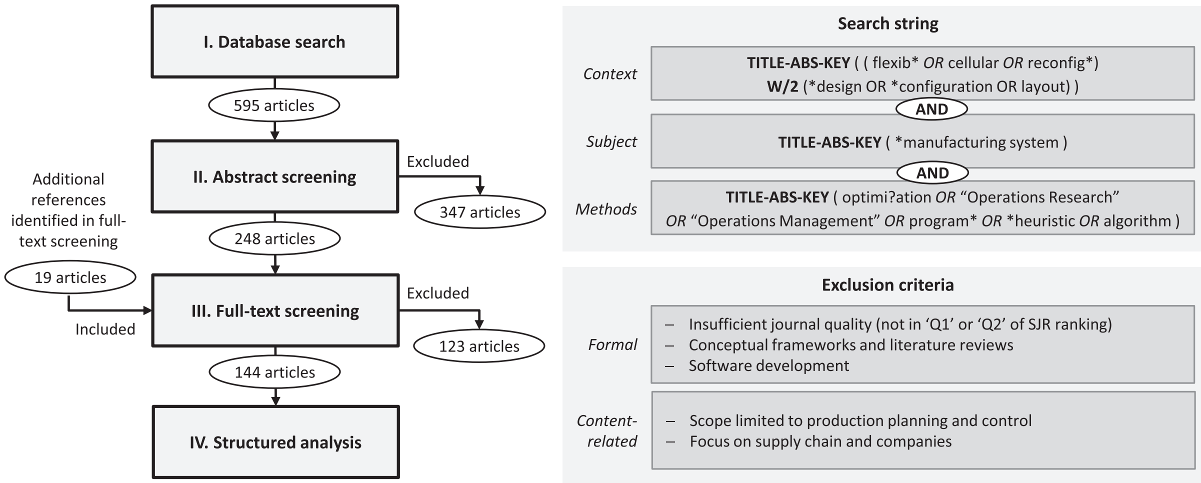

Fig. 1. Overview of the systematic search and screening process.

mastering the flexibility they provide is of utmost importance. Therefore, advanced analytical methods retain high standing. The article at hand serves this domain in providing a common understanding of flexibility in manufacturing system design.

3. Review method

A systematic approach was applied to ensure comprehensiveness and minimize potential bias regarding identifying, selecting, and analyzing relevant articles (Thies et al., 2019). The procedure comprises four steps (cf. Fig. 1). First, a database search was carried out in October 2021 and updated in December 2022 using Elsevier's Scopus database (www.scopus.com), which provides extensive coverage of peer-reviewed scientific literature and an advanced interface for detailed analysis and data export. The multi-level search string is composed of keywords that address the *subject* and the *context* of this review (i.e., flexibility in manufacturing system design) as well as the specific set of *methods* in the domain of Operations Research (e.g., optimization, heuristics, algorithms). The search string hedges against alternative spelling using single-character placeholders (e.g., '*optimi?ation*' to cover 'optimization' and 'optimisation') and multiple-character placeholders (e.g., '**heuristic*' to cover 'heuristic', 'matheuristic', and 'metaheuristic'). Additionally, proximity operators identify keywords close to one another (e.g., '*flexib* W/2 *design*' to yield '[…] design of flexible […]' or '[…] flexibility in design […]'). For a focus on recent publications, only articles published in this millennium are considered.

Next, the results from the database search underwent a two-stage screening process to exclude those articles not relevant to this review. These relate to formal criteria (i.e., insufficient quality of the journal, conceptual frameworks and literature reviews, articles describing software development) or content-related criteria (e.g., scope limited to production planning and control, focus on supply chain and company). The screening of titles, abstracts, and metadata already allowed the exclusion of many articles. The remaining articles underwent a full-text screening, in which further articles were excluded. Moreover, several additional articles that were identified in the references of the screened articles and considered relevant were included in this step.

Finally, the 144 articles in the review database were analyzed using a structured spreadsheet to extract the relevant data. Most importantly, each article's specific problem setting, manufacturing paradigm, objective, the considered flexibility types and the applicable limitations they suffer from, the decisions depicted in the mathematical models, and the applied Operations Research methods and solution approaches were collected.

4. Descriptive analysis of the review database

This section compiles aggregate information on the articles in the review database for descriptive analysis, referring to the publication output over time and the highly frequented publication venues. Additionally, initial insights are provided into the articles' problem setting regarding the degree of certainty and time reference, the pursued objectives, and the used methods.

Fig. 2 tallies the number of articles in this review by year of publication. It can be observed that flexibility in manufacturing system design received continuous attention during the past 20 years. 28 of the 144 articles in this review are associated with the FMS manufacturing paradigm, 29 with the RMS manufacturing paradigm, and 82 can be attributed to the CMS manufacturing paradigm.

The integration of Operations Research methods into approaches for designing manufacturing systems considering flexibility has been advanced mainly from the production research community, as can be concluded from the analysis of the contributing journals (cf. Fig. 3). The 144 articles were found in 38 contributing journals. While 17 journals published more than one article, 21 published one each. Among the top 17 journals, seven journals belong to the Management Science and Operations Research field according to the Scimago Journal Ranking SJR 2021, namely the International Journal of Production Research, European Journal of Operational Research, Computers and Operations Research, International Journal of Production Economics, Annals of Operations Research, Production Planning and Control, and International Journal of Management Science and Engineering Management. With a total of 12 articles, the European Journal of Operational Research is in the top four contributing journals, surpassed by the International Journal of Production Research (36 articles), the International Journal of Advanced Manufacturing Technology (24 articles), and Computers and Industrial Engineering (13 articles). Therefore, the design of manufacturing systems considering flexibility is an important field for Management Science and Operations Research approaches in conjunction with the engineering domains.

Fig. 4 illustrates the distribution of the articles in the review database regarding the degree of certainty and time reference. In most articles, deterministic problem settings are evaluated, pursuing static or dynamic approaches. Surprisingly, only 20 of 144 articles in the review database consider a stochastic problem setting.

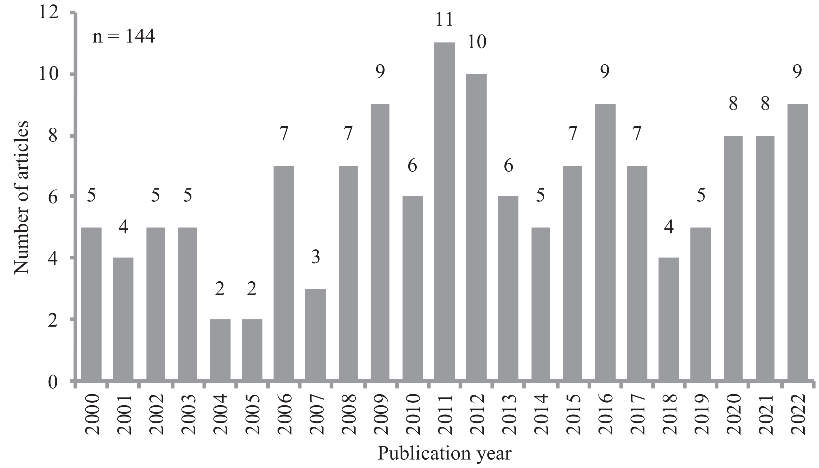

Fig. 2. Distribution of articles by publication year.

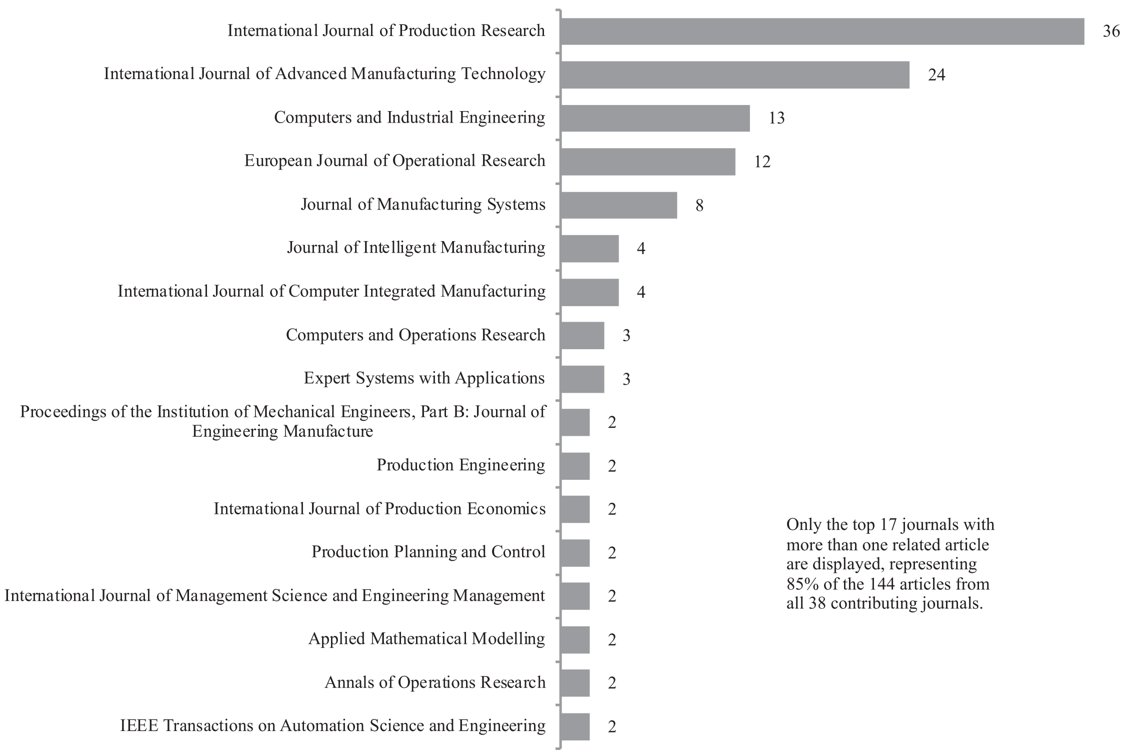

Fig. 3. Distribution of articles by contributing journals.

Among these, the most frequently considered stochastic parameter is the demand for products (Arzi, Bukchin & Masin, 2001; Kumar & Singh, 2018; Safaei et al., 2008), followed by the consideration of unreliable machines prone to failure (Aghajani et al., 2014; Das, Lashkari & Sengupta, 2006; Saeed Jabal Ameli & Arkat, 2008), and stochastic processing times (Ghezavati & Saidi-Mehrabad, 2011; Goli, Tirkolaee & Aydin, 2021).

A look at the objectives pursued in the articles (cf. Fig. 5) reveals the predominant consideration of performance-oriented (e.g., maximization of resource utilization or minimization of transport distances) and economic objectives (e.g., minimization of costs or maximization of profit). Only one article pursues a social objective and several performance-oriented objectives (Bortolini et al., 2021a). The authors strive to minimize the overall repetitive movements of workers and therefore consider aspects of ergonomics. Focusing on the ecological perspective, two articles aim to minimize the consumption of electrical energy (Kumar & Singh, 2018; Lamba et al., 2020), and one article strives to minimize hazardous liquid waste and greenhouse gasses (Khettabi, Benyoucef & Boutiche, 2021).

Various Operations Research methods are used to solve the associated manufacturing system design problems (cf. Table 2). Among the exact methods, mixed-integer, integer, and binary integer programming approaches are highly utilized and used in 47, 30, and 29 articles, respectively. Heuristic algorithms mainly refer to metaheuristics as problem-independent algorithmic frameworks that provide guidelines for algorithm development (Sörensen, 2015; Sörensen & Glover, 2013). Evolutionary algorithms and simulated annealing are most frequently applied, counting 45 and 23 occurrences. The construction and improvement procedures listed

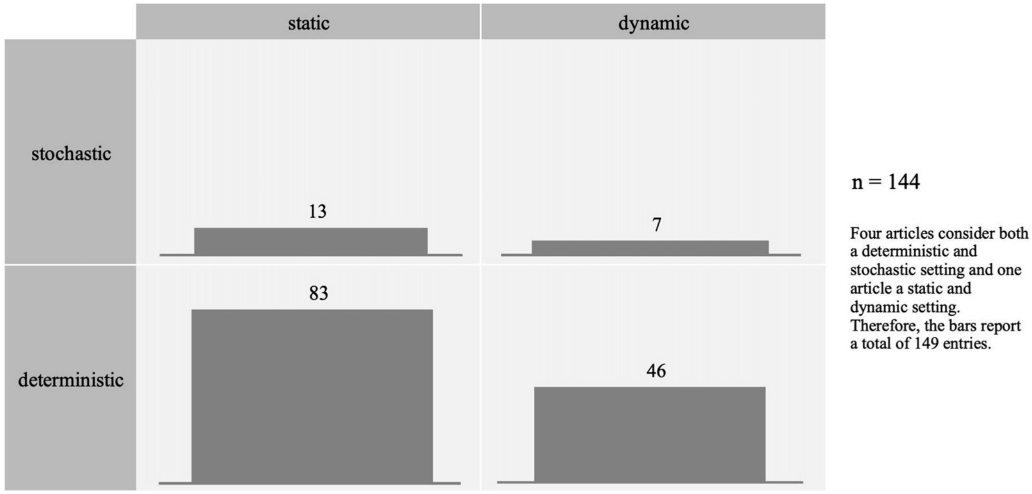

Fig. 4. Distribution of articles by degree of certainty and time reference.

Table 2
Number of articles using exact and heuristic methods.

Exact methods	Occurrences	Heuristic methods	Occurences
Mixed-integer programming	47	Evolutionary algorithm	45
Integer programming	30	Simulated annealing	23
Binary integer programming	29	Heuristic constructive procedure	24
Branch & Bound	2	Heuristic improvement procedure	15
Dynamic programming	2	Particle swarm optimization	7
Goal programming	2	Tabu search	4
Semidefinite programming	2	Ant colony optimization	2
Benders' decomposition	1	Scatter search	2
		Greedy randomized adaptive search procedure	1
		Machine learning	1

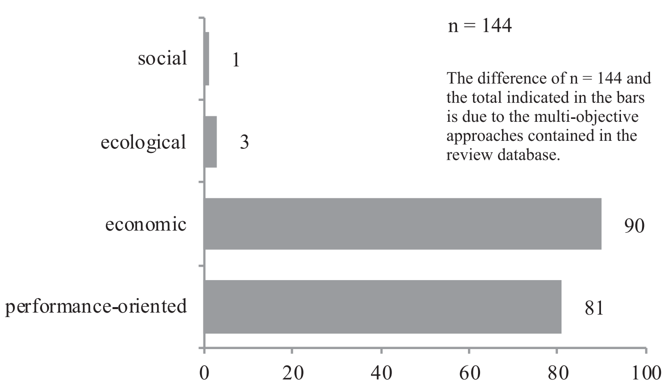

Fig. 5. Distribution of articles by pursued objectives.

in the table refer to independent approaches, i.e., methods of these types used in metaheuristics are not accounted for again in the number of construction and improvement procedures.

Surprisingly, 23 of 144 articles in the review database incorrectly classify the methods they develop. This mainly applies to integer or binary integer programming approaches that the authors classify as mixed-integer programming despite the absence of continuous variables. A comprehensive overview and a classification of the articles in the review database are provided in Table 3. A detailed discussion of the insights regarding the consideration of flexibility and the application of Operations Research methods follows in the next section.

5. Consideration of flexibility in the design of manufacturing systems

This section classifies the literature in the review database according to the types of flexibility and their attributes they consider. To this end, the concept of manufacturing flexibility is introduced and adapted in Section 5.1, which unites the different literature streams in the analysis. The identified flexibility types are attributed to two sets of flexibility types that guide the analyses (basic flexibility types, system flexibility types). Accordingly, insights into the approaches' consideration and management of basic flexibility types are provided in Sections 5.2–5.5, and system flexibility types are discussed in Sections 5.6–5.8. These sections initially *characterize the literature*. Subsequently, the associated Operations Research approaches are discussed with a particular focus on the *decisions*, *objectives*, *optimization methods*, and the consideration of *uncertainty*. Finally, *emerging topics* are identified.

5.1. Classification scheme for flexibility in the design of manufacturing systems

According to Kickert (1984), the flexibility of a system is its adaptability to a wide range of possible environments that it may encounter. Consequently, a flexible system must be capable of changing to deal with environmental changes. Due to the previously addressed increase in product variety and shortened product life cycles, such a necessity arises increasingly and relates particularly to the production stages of manufacturing corporations.

In this context, *manufacturing flexibility* can be defined as the ability of a manufacturing system to adjust manufacturing resources to cope with changing circumstances caused by the environment (Gupta & Goyal, 1989a; Sethi & Sethi, 1990) with no or only a few penalties in time, cost, or performance (Das, 2001; Upton, 1994). For the remainder of this contribution, manufacturing flexibility is therefore considered as the property of the manufacturing systems' machines, workers, stations (which we collectively refer to as *resources*), and material handling systems that are integrally designed and linked to each other to withstand vary-

Table 3
Overview of articles in the review database.

General information			Flexibility consideration				Problem setting		Objective					Decision classes					Applied OR methods	Computational study
Authors and year	Manufacturing paradigm	Machine flexibility	Labor flexibility	Operation flexibility	Material handling flexibility	System flexibilities	deterministic/ stochastic	static/ dynamic	performance-oriented	economic	ecological	social	No. of objectives	capacity decisions	layout decisions	configuration decisions	production planning decisions	control decisions		
Akturk and Turkcan (2000)	CMS	cap, mul		pre	full		Det	Sta		x			1	x	x			x	MIP, CH, IH	experiment
Logendran and Sirikrai (2000)	CMS	cap, mul		full	full		Det	Sta		x			1	x	x			x	IP, TS	experiment
Mak, Wong and Wang (2000)	CMS	mul		full	full		Det	Sta	x				1		x			x	EA	experiment
Songore and Songore (2000)	CMS	mul		full	full		Det	Sta	x				1		x			x	TS	experiment
Arzi, Bukchin and Masin (2001)	CMS	cap, mul		full	dis		Sto	Sta	x				2		x			x	IP, EA	experiment
Diallo M., Pierreval H., Quilliot A. (2001)	CMS	mul		seq	full		Sto	Dyn	x				1					x	CH, IH	illustrative
Wang, Wu and Liu (2001)	CMS	mul		dis	full	mix	Det	Dyn		x			1		x				BIP, SA	experiment
Saad, Baykasoglu and Gindy (2002)	CMS	cap, mul		dis	full	mix, pro, vol, exp	Sto	Dyn	x				4		x			x	BIP, CH	industrial
Solimanpur, Vrat and Shankar (2002)	CMS	mul		full	full		Det	Sta	x				1		x			x	ML	experiment
Vairaktarakis G.L., Cai X., Lee C.-Y. (2002)	CMS		mul	dis	full		Det	Sta	x				2		x			x	MIP, CH	experiment
Venkataramanaiah and Krishnaiah (2002)	CMS	mul		full	full		Det	Sta	x				1		x			x	CH, IH	experiment
Baykasoglu (2003)	CMS	mul		full	full		Det	Sta	x				1		x				SA	industrial
Chen (2003)	CMS	mul		full	full		Det	Sta	x				1		x			x	CH	experiment
Wang (2003)	CMS	mul		full	full		Det	Sta	x				1		x			x	BIP, CH	experiment
Xambre and Vilarinho (2003)	CMS	cap, mul		pre	full		Det	Sta	x				1		x			x	MIP, SA	illustrative
Jayaswal and Adil (2004)	CMS	cap, mul		full	full		Det	Sta		x			1	x	x			x	MIP, SA	experiment
Solimanpur, Vrat and Shankar (2004)	CMS	cap, mul		seq	dis		Det	Sta	x	x			4		x			x	BIP, EA	illustrative
Das, Lashkari and Sengupta (2006)	CMS	mul		seq	full		Det, Sto	Sta	x	x			2		x			x	BIP, SA(EA)	illustrative
Defersha and Chen (2006a)	CMS	cap, mul		full	full	mix, exp	Det	Dyn		x			1	x	x		x	x	MIP	experiment
Defersha and Chen (2006b)	CMS	cap, mul		full	full	mix, exp	Det	Dyn		x			1	x	x		x	x	MIP, EA	illustrative
Wu et al. (2006)	CMS	cap, mul		full	full		Det	Sta	x	x			2		x			x	BIP, EA	experiment
Arkat, Saidi and Abbasi (2007)	CMS	mul		dis	full		Det	Sta	x				1		x			x	SA	illustrative
Safaei, Saidi-Mehrabad and Babakhani (2007)	CMS	cap, mul, rel		dis	full	mix, exp	Sto	Dyn		x			1	x	x			x	IP	illustrative
Mahdavi, Shirazi and Paydar (2008)	CMS	mul		full	full		Det	Sta	x				1		x				CH	illustrative
Pillai and Subbarao (2008)	CMS	cap		full	full		Det	Sta		x			1	x	x			x	MIP, EA	experiment
Saeed Jabal Ameli and Arkat (2008)	CMS	cap, mul		dis	full		Det, Sto	Sta		x			1		x			x	BIP	illustrative
Safaei et al. (2008)	CMS	cap, mul, rel		dis	full	mix, exp	Sto	Dyn		x			1	x	x			x	IP	experiment

(*continued on next page*)

Table 3 (*continued*)

General information		Flexibility consideration					Problem setting		Objective					Decision classes					Applied OR methods	Computational study
Authors and year	Manufacturing paradigm	Machine flexibility	Labor flexibility	Operation flexibility	Material handling flexibility	System flexibilities	deterministic/ stochastic	static/ dynamic	performance-oriented	economic	ecological	social	No. of objectives	capacity decisions	layout decisions	configuration decisions	production planning decisions	control decisions		
Safaei, Saidi-Mehrabad and Jabal-Ameli (2008)	CMS	cap, mul, rel		dis	full	mix, pro, vol, exp	Det	Dyn		x			1	x	x			x	IP, SA	illustrative
Ah kioon, Bulgak and Bektas (2009a)	CMS	cap, mul, rel		dis	full	mix, vol, exp	Det	Dyn		x			1	x	x		x	x	MIP	experiment
Ah kioon, Bulgak and Bektas (2009b)	CMS	cap, mul, rel		pre	full	mix, vol, exp	Det	Dyn		x			1	x	x		x	x	IP	experiment
Ariafar and Ismail (2009)	CMS			full	full		Det	Sta	x				1		x				MIP, SA	experiment
Rezazadeh et al. (2009)	CMS	cap, mul, rel	cap, mul, rel	dis	full	mix, vol	Det	Dyn		x			1		x		x	x	IP, PSO	experiment
Satoglu and Suresh (2009)	CMS	cap, mul	cap, mul	full	full		Sto	Sta	x	x			3	x	x	x		x	IP, GP	industrial
Wang, Tang and Yung (2009)	CMS	cap, mul, rel		dis	full	mix, exp	Det	Dyn	x	x			3	x	x			x	IP, SS	experiment
Mahdavi et al. (2010)	CMS	cap, mul, rel	cap, mul, rel	full	full	mix, vol, exp	Det	Dyn		x			1	x	x		x	x	IP	illustrative
Paydar et al. (2010)	CMS	mul		dis	full		Det	Sta		x			1		x			x	SA	experiment
Satoglu, Durmusoglu and Ertay (2010)	CMS	cap, mul		full	full		Det	Sta	x				1	x	x			x	IP, CH	illustrative
Süer, Huang and Maddisetty (2010)	CMS	cap		dis	dis		Sto	Sta	x				2					x	BIP, CH	illustrative
Chung, Wu and Chang (2011)	CMS	cap, mul		seq	full		Det	Sta		x			1		x			x	BIP, TS(EA)	experiment
Das and Abdul-Kader (2011)	CMS	cap, mul, rel		seq	full	mix, exp	Sto	Dyn	x	x			2	x	x			x	MIP	illustrative
Ghezavati and Saidi-Mehrabad (2011)	CMS	cap, mul		full	dis		Sto	Sta	x				1		x		x	x	MIP, EA(SA)	experiment
Ghotboddini, Rabbani and Rahimian (2011)	CMS	cap, mul, rel	cap, mul, rel	dis	full	mix, exp	Det	Dyn	x	x			2	x	x			x	MIP, BD	illustrative
Javadian et al. (2011)	CMS	cap, mul, rel		full	full	mix, vol, exp	Det	Dyn	x	x			2	x	x		x	x	IP, EA	illustrative
Jolai, Taghipour and Javadi (2011)	CMS	mul		full	full		Det	Sta		x			1		x				BIP, PSO	experiment
Mahdavi et al. (2011)	CMS	cap, mul, rel	cap, mul, rel	full	dis	mix, vol, exp	Det	Dyn	x	x			2		x		x	x	IP, GP	illustrative
Rafiee et al. (2011)	CMS	cap, mul, rel		seq	full	mix, pro, vol, exp	Det	Dyn		x			1	x	x		x	x	MIP, PSO	illustrative

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Table 3 (*continued*)

General information		Flexibility consideration					Problem setting		Objective					Decision classes					Applied OR methods	Computational study
Authors and year	Manufacturing paradigm	Machine flexibility	Labor flexibility	Operation flexibility	Material handling flexibility	System flexibilities	deterministic/ stochastic	static/ dynamic	performance-oriented	economic	ecological	social	No. of objectives	capacity decisions	layout decisions	configuration decisions	production planning decisions	control decisions		
Rezaeian et al. (2011)	CMS	mul		full	full	mix	Det	Dyn		x			1	x				x	BIP, EA(ML)	experiment
Saxena and Jain (2011)	CMS	cap, mul, rel,		full	full	mix, vol, exp	Det	Dyn		x			1	x	x		x	x	IP	experiment
Arkat, Hosseinabadi Farahani and Hosseini (2012)	CMS	mul		pre	full		Det	Sta	x	x			2		x			x	IP, EA	experiment
Egilmez, Süer and Huang (2012)	CMS	cap, mul		full	dis		Sto	Sta	x				1					x	BIP	experiment
Kia et al. (2012)	CMS	cap, mul, rel		dis	full	mix, pro, exp	Det	Dyn		x			1	x	x			x	IP, SA	experiment
Saraç and Ozcelik (2012)	CMS	mul		full	full		Det	Sta	x				1		x				EA	experiment
Tavakkoli-Moghaddam et al. (2012)	CMS	cap, mul		dis	full		Det	Sta	x	x			4		x			x	MIP, SS	experiment
Fan and Feng (2013)	CMS	cap, mul	cap, mul	pre	full		Det	Sta	x	x			6		x	x		x	IP, EA	industrial
Javadi et al. (2013)	CMS	cap, mul		dis	full		Det	Sta		x			1	x	x				MIP	illustrative
Liu et al. (2013)	CMS		cap, mul	full	dis		Det	Sta	x	x			2		x			x	BIP, CH	illustrative
Zeidi et al. (2013)	CMS	mul		full	full	mix	Det	Dyn	x	x			2	x	x			x	BIP, EA(ML)	experiment
Aghajani et al. (2014)	CMS	cap, mul, rel		full	full	mix, vol	Sto	Dyn	x	x			3		x		x	x	IP, EA	experiment
Egilmez and Süer (2014)	CMS	cap, mul		full	dis		Sto	Sta	x				2					x	BIP	experiment
Kia et al. (2014)	CMS	cap, mul, rel		dis	full	mix, exp	Det	Dyn		x			1	x	x			x	IP, EA	experiment
Mohammadi and Forghani (2014)	CMS	cap, mul		seq	full		Det	Sta		x			1		x		x	x	MIP, EA	experiment
Deep and Singh (2015)	CMS	cap, mul, rel		full	full	mix, vol, exp	Det	Dyn		x			1	x			x	x	IP, EA	experiment
Erenay et al. (2015)	CMS	cap, mul		full	dis		Sto	Sta	x				1	x				x	CH, IH, BIP	experiment
Forghani, Mohammadi and Ghezavati (2015)	CMS	mul		full	full		Det	Sta		x			1		x				MIP, CH, IH	experiment
Renna and Ambrico (2015)	CMS	cap, mul, rel, rec		dis	full	mix, pro	Sto	Dyn		x			3		x	x	x	x	IP, MIP	illustrative

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Table 3 (*continued*)

General information		Flexibility consideration					Problem setting		Objective					Decision classes					Applied OR methods	Computational study
Authors and year	Manufacturing paradigm	Machine flexibility	Labor flexibility	Operation flexibility	Material handling flexibility	System flexibilities	deterministic/ stochastic	static/ dynamic	performance-oriented	economic	ecological	social	No. of objectives	capacity decisions	layout decisions	configuration decisions	production planning decisions	control decisions		
Won and Logendran (2015)	CMS	cap, mul		full	full		Det	Sta	x				2		x			x	BIP, CH	experiment
Alhourani (2016)	CMS	cap, mul		dis	full		Det	Sta	x	x			3		x			x	CH, IH	illustrative
Aljuneidi and Bulgak (2016)	CMS	cap, mul, rel		full	full	mix, vol, exp	Det	Dyn		x			1	x	x		x		MIP	illustrative
Bayram and Şahin (2016)	CMS	cap, mul, rel		dis	full	mix, vol, exp	Det	Dyn		x			1	x	x			x	IP, EA(LP), SA(LP)	experiment
Ghosh, Doloi and Dan (2016)	CMS	mul		full	full		Det	Sta	x				1		x				EA	experiment
Mehdizadeh, Daei Niaki and Rahimi (2016)	CMS	cap, mul, rel	cap, mul, rel	seq	full	mix, vol	Det	Dyn	x	x			2	x	x		x	x	IP, EA	experiment
Mohammadi and Forghani (2016)	CMS	mul		full	full		Det	Sta	x	x			2		x				IP, SA(DP)	experiment
Aljuneidi and Bulgak (2017)	CMS	cap, mul, rel		full	full	mix, vol, exp	Det	Dyn		x			1	x	x		x		MIP	experiment
Defersha and Hodiya (2017)	CMS	cap, mul		seq	full		Det	Sta		x			2		x			x	MIP, SA	illustrative
Kumar and Singh (2017)	CMS	mul, rel		full	full		Det	Dyn		x			1		x				MIP, CH	experiment
Shafigh, Defersha and Moussa (2017)	CMS	cap, mul, rel		dis	full	mix, vol	Det	Dyn		x			1		x		x	x	MIP, SA(LP)	illustrative
Kumar and Singh (2018)	CMS	mul		full	full		Det, Sto	Sta		x	x		2		x				BIP, SA	experiment
Liu, Wang and Zhou (2019)	CMS	cap, rec	cap, mul, rel, rec	dis	full	mix, vol	Det	Dyn		x			1		x	x		x	BIP, CH, IH	experiment
Deep (2020)	CMS	cap, mul, rel	cap, mul, rel	full	full	mix, vol, exp	Det	Dyn		x			1	x	x		x	x	MIP, EA(SA)	experiment
Kia (2020)	CMS	cap, mul, rel		dis	full	mix, vol, exp	Det	Dyn		x			1	x	x		x		IP, EA	experiment
Lamba et al. (2020)	CMS	mul, rel		full	full	mix	Det	Dyn		x	x		4		x			x	BIP, SA	experiment
Rahimi, Arkat and Farughi (2020)	CMS	cap, mul		pre	full		Det	Sta	x				1	x	x			x	MIP, SA	experiment
Xue and Offodile (2020)	CMS	cap, mul, rel		dis	full	mix, vol, exp	Det	Dyn		x			1	x	x		x		MIP	industrial

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Table 3 (*continued*)

General information		Flexibility consideration					Problem setting		Objective					Decision classes					Applied OR methods	Computational study
Authors and year	Manufacturing paradigm	Machine flexibility	Labor flexibility	Operation flexibility	Material handling flexibility	System flexibilities	deterministic/ stochastic	static/ dynamic	performance-oriented	economic	ecological	social	No. of objectives	capacity decisions	layout decisions	configuration decisions	production planning decisions	control decisions		
Goli, Tirkolaee and Aydin (2021)	CMS	mul	mul	full	full		Sto	Sta		x			1		x			x	MIP, EA	experiment
Mansour, Afefy and Taha (2022)	CMS	cap, mul	cap, mul	seq	full		Det	Sta		x			1		x			x	BIP, CH	industrial
Salimpour, Pourvaziri and Azab (2021)	CMS	mul		dis	full	mix	Det	Dyn	x				2		x				MIP, EA	experiment
Hottenrott, Schiffer and Grunow (2023)	CMS	cap, mul		pre	ser		Sto	Sta	x				1					x	MIP, BB	experiment
Kumar A., Jacobson S.H., Sewell E.C., 2000	FMS	mul		pre	ser		Det	Sta	x				1		x			x	CH, BB	experiment
Potts and Whitehead (2001)	FMS	cap, mul		dis	ser		Det	Sta	x				2		x			x	BIP	industrial
Saitou, Malpathak and Qvam (2002)	FMS	cap, mul		full	full	mix, pro, exp	Det	Dyn		x			1	x				x	EA	illustrative
Chaieb and Korbaa (2003)	FMS	mul		pre	ser		Det	Sta	x				1		x				MIP	illustrative
Solimanpur, Vrat and Shankar (2005)	FMS	mul		full	ser		Det	Sta	x				1		x				BIP, ACO	experiment
Yang, Peters and Tu (2005)	FMS	mul		full	ser		Det	Sta		x			1		x				MIP, SA	illustrative
Amaral (2006)	FMS	mul		full	ser		Det	Sta	x				1		x				MIP	experiment
Chae and Peters (2006a)	FMS	mul		full	ser		Det	Sta		x			1		x				SA	experiment
Satheesh Kumar, Asokan and Kumanan (2008)	FMS	multilple capabili-ties		dis	ser		Det	Sta	x				1		x				PSO	illustrative
Tolio and Valente (2009)	FMS	cap, mul		full	full	mix, pro, exp	Det, Sto	Dyn		x			1	x					MIP	industrial
Ficko et al. (2010)	FMS	mul		full	full		Det	Sta		x			1		x				PSO	experiment

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Table 3 (*continued*)

General information			Flexibility consideration				Problem setting		Objective					Decision classes					Applied OR methods	Computational study
Authors and year	Manufacturing paradigm	Machine flexibility	Labor flexibility	Operation flexibility	Material handling flexibility	System flexibilities	deterministic/ stochastic	static/ dynamic	performance-oriented	economic	ecological	social	No. of objectives	capacity decisions	layout decisions	configuration decisions	production planning decisions	control decisions		
Datta, Amaral and Figueira (2011)	FMS	mul		full	ser		Det	Sta	x				1		x				EA	experiment
Ozcelik (2012)	FMS	mul		full	ser		Det	Sta	x				1		x				EA	experiment
Tolio and Urgo (2013)	FMS	cap, mul, rel, rec		pre	ser	pro, exp	Det	Dyn		x			2	x				x	MIP	industrial
Tubaileh (2014)	FMS	mul		full	ser		Det	Sta	x				1		x				IP, SA	experiment
Hungerländer and Anjos (2015)	FMS	mul		full	ser		Det	Sta	x				1		x				SDP	experiment
Saravanan and Kumar (2015)	FMS	mul		dis	ser		Det	Sta	x				2		x				EA	experiment
Mallikarjuna, Veeranna and Reddy (2016)	FMS	cap, mul		full	ser		Det	Sta	x				1		x				EA, SA	experiment
Tubaileh and Siam (2017)	FMS	mul		full	ser		Det	Sta	x				1		x				SA, ACO	experiment
Anjos, Fischer and Hungerländer (2018)	FMS	mul		full	ser		Det	Sta	x				1		x				BIP, SDP	experiment
Amaral (2019)	FMS	mul		full	ser		Det	Sta	x				1		x				MIP	experiment
Fischer, Fischer and Hungerländer (2019)	FMS	mul		full	ser		Det	Sta	x				1		x				MIP	experiment
Alduaij and Hassan (2020)	FMS	cap, mul		dis	full		Det	Sta		x			1	x	x			x	MIP	experiment
Pourvaziri et al. (2022)	FMS	cap, mul		full	full	mix	Det	Dyn	x				1		x			x	MIP, EA(TS)	experiment
Amaral (2022)	FMS	mul		full	ser		Det	Sta	x				1		x				IH(LP)	experiment
Cravo and Amaral (2022)	FMS	mul		full	ser		Det	Sta	x				1		x				IH	experiment
Guan et al. (2022)	FMS	mul		full	ser	mix, pro	Det	Dyn		x			1		x				MIP, EA	experiment
Qi, Hao and Yuan (2023)	FMS	mul		full	ser		Det	Dyn		x			1		x				MIP, IH	experiment

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Table 3 (*continued*)

General information		Flexibility consideration					Problem setting		Objective					Decision classes					Applied OR methods	Computational study
Authors and year	Manufacturing paradigm	Machine flexibility	Labor flexibility	Operation flexibility	Material handling flexibility	System flexibilities	deterministic/ stochastic	static/ dynamic	performance-oriented	economic	ecological	social	No. of objectives	capacity decisions	layout decisions	configuration decisions	production planning decisions	control decisions		
Youssef and ElMaraghy (2006)	RMS	cap, mul, rec		pre	ser		Det	Sta		x			1	x	x	x		x	IP, EA	illustrative
Spicer and Carlo (2007)	RMS	cap, mul, rel, rec		full	full	exp, pro	Det	Dyn		x			1	x	x				DP, DP(IP)	illustrative
Youssef and ElMaraghy (2008)	RMS	cap, mul, rec		pre	ser		Det	Sta		x			1	x	x	x		x	EA, TS	illustrative
Dou, Dai and Meng (2009a)	RMS	cap, mul, rel, rec		pre	ser	mix, exp	Det	Dyn		x			1		x			x	CH, IH	industrial
Dou, Dai and Meng (2009b)	RMS	cap, mul, rel, rec		pre	ser	mix, exp	Det	Dyn		x			1		x			x	EA	industrial
Dou, Dai and Meng (2010)	RMS	cap, mul, rel, rec		pre	ser	mix, exp	Det	Dyn					1	x	x			x	BIP, EA	industrial
Essafi, Delorme and Dolgui (2012)	RMS	cap, mul, rec		pre	ser		Det	Sta	x	x			1	x	x			x	GRASP	industrial
Goyal, Jain and Jain (2012)	RMS	cap, mul, rec		full	ser		Det	Sta	x	x			3		x	x			EA	illustrative
Saxena and Jain (2012)	RMS	cap, mul, rel, rec		pre	ser	mix, exp	Det	Dyn		x			1	x	x	x		x	CH, IH	illustrative
Wang and Koren (2012)	RMS	cap, mul		pre	ser		Det	Sta	x				1	x				x	IP, EA	industrial
Bensmaine, Dahane and Benyoucef (2013)	RMS	cap, mul, rec		full	full		Det	Sta	x	x			2	x		x			EA	illustrative
Goyal and Jain (2015)	RMS	cap, mul, rec		seq	ser		Det	Sta	x	x			4		x			x	PSO	experiment
Dou, Li and Su (2016)	RMS	cap, mul, rel, rec		pre	ser	mix, exp	Det	Dyn	x	x			2	x	x	x		x	MIP, EA	illustrative
Battaïa, Dolgui and Guschinsky (2017)	RMS	mul, rec		pre	ser		Det	Sta		x			1		x	x		x	MIP, CH, IH	industrial
Koren, Wang and Gu (2017)	RMS	cap, mul, rec		pre	ser		Det	Sta	x				1	x				x	MIP, EA	industrial
Ashraf and Hasan (2018)	RMS	cap, mul, rec		pre	ser		Det	Sta	x	x			4		x	x		x	EA	industrial

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Table 3 (*continued*)

General information		Flexibility consideration					Problem setting		Objective					Decision classes					Applied OR methods	Computational study
Authors and year	Manufacturing paradigm	Machine flexibility	Labor flexibility	Operation flexibility	Material handling flexibility	System flexibilities	deterministic/ stochastic	static/ dynamic	performance-oriented	economic	ecological	social	No. of objectives	capacity decisions	layout decisions	configuration decisions	production planning decisions	control decisions		
Moghaddam, Houshmand and Fatahi Valilai (2018)	RMS	cap, mul, rec		dis	ser		Det	Sta		x			1			x		x	IP	illustrative
Haddou Benderbal and Benyoucef (2019)	RMS	mul, rec		dis	full	pro	Det	Sta	x				2		x	x			SA	illustrative
Huang, Wang and Yan (2019)	RMS	mul, rec		dis	ser		Det	Sta	x				2		x			x	CH, IH	illustrative
Huang and Yan (2020)	RMS	cap, mul, rec		pre	ser		Det	Sta	x				2		x			x	CH, IH	industrial
Moghaddam et al. (2020)	RMS	cap, mul, rec		dis	ser		Det	Sta, Dyn		x			1	x		x			IP	illustrative
Bortolini et al. (2021a)	RMS	cap, mul, rec	cap,mul, rel	full	full	mix	Det	Dyn	x			x	2			x		x	BIP	illustrative
Bortolini et al. (2021b)	RMS	cap, mul, rec		full	full	mix	Det	Dyn	x				3			x		x	BIP	industrial
Campos Sabioni, Daaboul and Le Duigou (2022)	RMS	mul, rel, rec		pre	full	pro	Det	Sta		x			1		x	x		x	BIP, EA	industrial
Khettabi, Benyoucef and Boutiche (2021)	RMS	mul, rec		pre	full		Det	Sta	x	x	x		4			x		x	BIP, EA	experiment
Khan (2022)	RMS	cap, mul, rec		full	full	pro, vol, exp	Det	Dyn	x	x			4		x	x		x	MIP, EA(SA)	industrial
Mansour, Afefy and Taha (2023)	RMS	cap, mul, rel, rec		dis	full	mix, pro, vol, exp	Det	Dyn		x			3		x	x		x	MIP	experiment
Yang et al. (2022)	RMS	cap, mul		full	ser		Det	Sta	x	x			3		x			x	MIP, PSO	illustrative
Zhu et al. (2022)	RMS	cap, mul	cap, mul	full	full		Det	Sta	x	x			3					x	MIP, EA	illustrative

Machine/Labor flexibility: cap = capacity of machines/workers is considered; mul = multiple capabilities of machines/workers are considered; rel = machines/workers can be relocated; rec = machines/workers can be reconfigured
Material handling flexibility: full = each resource can freely be accessed from other resources; ser = material flows strictly follows a serial arrangement of stations; dis = products cannot be transferred between resources of different stations
Operation flexibility: full = no predetermined sequences need to be considered between operations; pre = precedence relations between operations need to be complied with; seq = prespecified sequences of operations are decided on; dis = operations need to be executed in a fixed order
System flexibilities: mix = mix flexibility is considered; pro = product flexibility is considered; vol = volume flexibility is considered; exp = expansion flexibility is considered
Problem setting: Det = Deterministic; Sto = Stochastic; Sta = Static; Dyn = Dynamic
Exact approaches: LP = Linear programming; IP = Integer programming; BIP = Binary integer programming; MIP = Mixed-integer programming; SDP = Semidefinite programming; BB = Branch & Bound; BD = Benders' decomposition; DP = Dynamic programming; GP = Goal programming
(Meta)heuristics: TS = Tabu search; EA = Evolutionary algorithm; SA = Simulated annealing; SS = Scatter search; PSO = Particle swarm optimization; ACO = Ant colony optimization; GRASP = Greedy randomized adaptive search procedure; CH = Heuristic constructive procedure; IH = Heuristic improvement procedure; ML = Machine learning; x(y) = Hybrid approach integrating components from y into an x framework algorithm
Computational study: illustrative = few instances are solved to validate the approach; experiment = several systematically generated instances are solved; industrial = the approach is applied to a real-world problem setting

Table 4
Flexibility types considered for the design of manufacturing systems.

Flexibility types		Reference	Description
Basic flexibilities	Machine flexibility	Resources	Operations machines can perform, processing times, machine mobility
	Labor flexibility	Resources	Operations workers can perform, processing times, worker mobility
	Operation flexibility	Products	Sequence alternatives of operations
	Material handling flexibility	Material handling systems	Material flow alternatives of products
System flexibilities	Mix flexibility	All	Ability to respond to demand changes in the mix of products
	Product flexibility	All	Ability to include unconsidered products to the product mix
	Volume flexibility	All	Ability to respond to changes in product volume (operational)
	Expansion flexibility	All	Ability to respond to changes in product volume (tactical)

ing production environments. To this end, manufacturing flexibility consists of a combination of different *flexibility types* which coexist and interact in the manufacturing system relating to aspects of the resources, the material handling system, and the products.

The abstract nature of manufacturing flexibility and the contained flexibility types suggest these terms' complex and multidimensional character. Consequently, literature investigating these concepts has discussed the ambiguous definitions and classifications of flexibility types composing manufacturing flexibility. Over 50 terms for flexibility types originate from different taxonomic or conceptual contributions to the concept of manufacturing flexibility, addressing it from different perspectives and with alternative scopes (Pérez Pérez, Serrano Bedia & López Fernández, 2016; Sethi & Sethi, 1990). Pérez Pérez et al. (2016) present the most complete and recognized classification of flexibility types in the context of manufacturing flexibility. In total, 62 taxonomic articles are considered, 26 different flexibility types are defined, and consensus definitions unite the flexibility types and the associated terms of the different literature streams.

For the contribution at hand, a general understanding of manufacturing flexibility and the flexibility types is required to unite literature contributing to different manufacturing paradigms. To this end, this article focuses on eight flexibility types inherent to individual manufacturing systems (i.e., neglecting flexibility relating to the supply chain or individual suppliers) and are directly related to manufacturing system design. The flexibility types considered for the design of manufacturing systems are based on the consensus definition found by Pérez Pérez et al. (2016). They are described in the following and summarized in Table 4.

The flexibility types are classified into static *basic flexibilities* and dynamic *system flexibilities*. The four basic flexibilities, on the one hand, are inherent to the resources of the manufacturing systems, the material handling systems, and the products to be produced. Without their explicit consideration, they are predominantly assumed as exhaustively available. However, they may become restricted by assumptions of the specific manufacturing environment or the considered manufacturing paradigm. For example, in the mindset of modeling practitioners, machines may be assumed to be exhaustively flexible and high-paced resources taking unlimited work unless their consideration details their applicable limitations. On the other hand, the four system flexibilities are enabled based on the extent of the available basic flexibilities and allow the manufacturing system to react in a dynamic environment.

The basic flexibilities are introduced in the following. *Machine flexibility* refers to the inherent capabilities of machines to perform different operations during the manufacturing process within corresponding processing times. It further describes the machines' ability to be assigned and relocated in the manufacturing system. Accordingly**,** *labor flexibility* refers to the range of operations a worker can perform within corresponding processing times and the workers' abilities to be assigned and relocated in the manufacturing system. These flexibility types relate to the resources of manufacturing systems. *Operation flexibility* describes the ability to change the sequence of operations required to manufacture each product during the manufacturing process. It, therefore, relates to the structure of the considered products and the exploitability of their inherent degrees of freedom. *Material handling flexibility* is inherent to the material handling system and describes the ability of the manufacturing system to transport workpieces between resources.

The basic flexibilities jointly enable the following types of dynamic system flexibility. On the one hand, the *mix flexibility* of a manufacturing system relates to its capability to respond quickly and economically to demand variations in the current product mix. *Product flexibility*, on the other hand, describes the ease with which new products can be added or substituted from the current manufacturing process. The difference between both flexibility types is based on the familiarity of the considered products within the product portfolio. While mix flexibility addresses a shift of product volume for prespecified products within the portfolio, adding formerly unconsidered products to the portfolio represents enhanced product flexibility. *Volume flexibility* of a manufacturing system describes its ability to be operated economically at different output levels from a short-term perspective maintaining the design as installed beforehand. Therefore, it relates to the exploitability of operational degrees of freedom. From a mid-term perspective, *expansion flexibility* describes the ability to operate economically at different output levels in which resources or material handling systems may be added to or removed from the existing system. It, therefore, relates to the exploitability of tactical degrees of freedom.

Based on the theoretical framework of manufacturing flexibility and the flexibility types relevant to manufacturing system design, the current literature addressing methodological approaches from Operations Research to design manufacturing systems of different manufacturing paradigms (FMS, CMS, RMS) are united. The remainder of Section 5 is structured accordingly (cf. Fig. 6).

5.2. Machine flexibility

5.2.1. Characterization of literature

Machine flexibility refers to the inherent capabilities of machines to perform different operations during the manufacturing process. As 142 of 144 articles of the review database consider machines, they are the most commonly considered resource. Accordingly, the limitations of machine flexibility find much attention. In the analyzed articles, the flexibility of machines is restricted to a large extent, citing various reasons.

Limitations of machine flexibility may arise from assumptions about the *capacity supply* of machines and the associated anticipation of their utilization. Therefore, machine flexibility may be restricted by a maximum permittable operation time per machine and period (Bortolini et al., 2021a; Khan, 2022; Potts and Whitehead, 2001; Wang and Koren, 2012). 89 of 144 articles of the review database consider the capacity supply of machines. When considering performance-oriented objectives, the high utilization

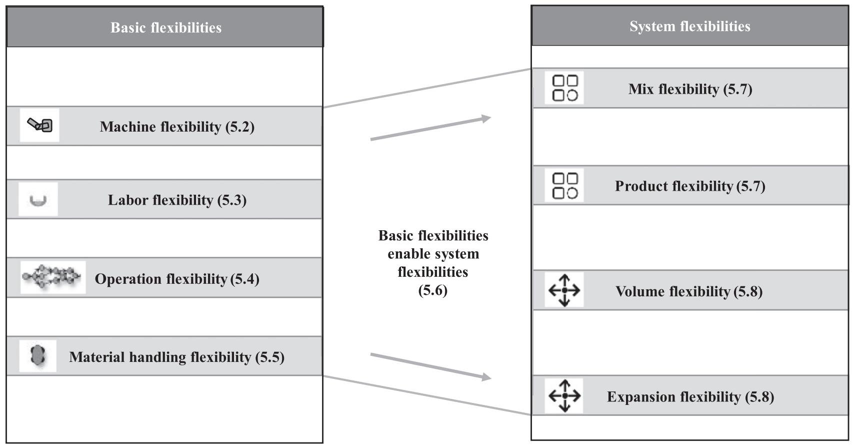

Fig. 6. Structure of Section 5 organized by flexibility types.

of machines can be enforced by minimizing the required time for producing a predetermined volume of products (Ghotboddini, Rabbani & Rahimian, 2011; Mehdizadeh, Daei Niaki & Rahimi, 2016; Wang, Tang & Yung, 2009). In cases of restricted capacity supply, the *processing times* associated with the required operations have to be considered. The processing times may either depend on the specific combination of machine and product (Bortolini et al., 2021b; Defersha and Chen, 2006a; Kumar A., Jacobson S.H., Sewell E.C., 2000) or remain identical (Essafi, Delorme & Dolgui, 2012; Shafigh, Defersha & Moussa, 2017; Süer, Huang & Maddisetty, 2010). Additionally, machines may suffer from a limited *capability to execute different operations* of the desired products. Machine flexibility may be limited to only one operation machines can execute (3 of 144 articles), indicating a strong specialization of machinery (Akturk & Turkcan, 2000; Huang & Yan, 2020; Solimanpur, Vrat & Shankar, 2005). Alternatively, machines may serve multiple purposes if more than one operation can be conducted (141 of 144 articles) (Ah kioon, Bulgak & Bektas, 2009b; Goli, Tirkolaee & Aydin, 2021; Mak, Wong & Wang, 2000).

When evaluating the maintained degree of machine flexibility, many articles refer to a conflict between costs and flexibility and integrate this tradeoff into their decisions. In doing so, an economically beneficial extent of machine flexibility can be determined. When considering machines with different extent of capabilities or different processing times, *machine purchase costs* (Moghaddam et al., 2020; Safaei et al., 2008; Saitou, Malpathak & Qvam, 2002) or *machine operation costs* may account for the associated degree of machine flexibility (Arzi, Bukchin & Masin, 2001; Mahdavi et al., 2010; Mansour, Afefy & Taha, 2022).

5.2.2. Operations Research approaches

The *decisions* pertaining to machine flexibility primarily concern the selection of the number and type of machines utilized in the manufacturing system to achieve the desired production level and meet the desired objectives. In the predominantly deterministic settings in the review database, the capabilities to conduct operations and their efficiency in terms of processing times of machines are known and have to be considered during manufacturing system design. Machine flexibility is crucial to these decisions, as tradeoffs between economic characteristics (e.g., high investment in machines with a broader range of capabilities) and performance characteristics (e.g., high efficiency of specialized machines) must be considered. While most articles do not explicitly consider the shopfloor, 12 of 144 articles additionally decide on the number of available stations and thus account for the space requirements for machine deployment (Akturk & Turkcan, 2000; Dou, Dai & Meng, 2010; Erenay et al., 2015; Essafi, Delorme & Dolgui, 2012; Javadi et al., 2013; Rahimi, Arkat & Farughi, 2020; Rezaeian et al., 2011; Satoglu & Suresh, 2009; Tolio & Valente, 2009; Youssef & ElMaraghy, 2006; Youssef & ElMaraghy, 2008; Zeidi et al., 2013). Both decisions relating to stations and machines determine the *capacity* manufacturing systems can provide.

Articles relating to machine flexibility mainly pursue economic *objectives* to minimize the total costs induced by machine deployment. Thus, the consideration of the economic aspects of machine flexibility is well-established. Additionally to the economic aspects, few articles consider performance-oriented objectives (Bensmaine, Dahane & Benyoucef, 2013; Das & Abdul-Kader, 2011; Dou, Li & Su, 2016; Ghotboddini, Rabbani & Rahimian, 2011; Javadian et al., 2011; Mehdizadeh, Daei Niaki & Rahimi, 2016; Satoglu & Suresh, 2009; Wang, Tang & Yung, 2009). The performance-oriented objectives comprise the maximization of machine utilization, the minimization of machine idle time, and the total completion time of production. Noticeably, neither social nor ecological objectives are considered.

Only mixed-integer programming (MIP) and integer programming approaches (IP) are proposed for the applied exact *optimization methods*. It stands out that the exact optimization methods are often combined with an additional heuristic approach to solve large problem instances.

Several articles investigate the economic design of CMS while deciding on machine selection. Logendran and Sirikrai (2000) integrate decisions about subcontracting by formulating an IP and proposing six adaptations of tabu search (TS). Jayaswal and Adil (2004) formulate an IP and apply a simulated annealing algorithm (SA) with an integrated local search heuristic. They economically assess machine flexibility by enabling machine duplicate purchases to facilitate additional routes during production. Javadi et al. (2013) additionally decide on the number of opened stations. In their approach, machines of different dimensions are grouped into stations. Therefore, they decide on the dimension of the stations based on the assigned machines. Moreover, the stations contain drop-off points for material transfer and can be positioned and oriented on the shop floor. An MIP is presented to depict and solve this problem. However, the approach is only suitable for solving small instances, and no heuristic approach is provided. Erenay et al. (2015) also decide on the number of opened stations and their specialization, as they can either be dedicated to single or multiple products. The authors formulate an IP and develop a multi-stage heuristic. Rahimi, Arkat and Farughi (2020) propose an MIP to simultaneously decide on station opening, the number and type of machines, and the operation-to-machines assignment. Several heuristics are proposed.

Regarding RMS approaches, various articles investigate their economic design considering machine selection and thus refer to machine flexibility. Youssef and ElMaraghy (2006) investigate the design of RMS flowlines using an MIP and applying an evolutionary algorithm (EA) that encodes binary decisions into continuous variables to generate faster solutions. Youssef and ElMaraghy (2008) extend the investigation by applying an EA and a TS. Dou, Dai and Meng (2010) formulate an IP and propose an EA. Essafi, Delorme and Dolgui (2012) extend the economic objective by considering the workload balancing of stations with an ε-constraint method. They formulate an MIP and suggest using a greedy randomized adaptive search procedure. Wang and Koren (2012) consider the design of RMS flowlines and decide upon the number of deployed machines and the operation-to-machines assignment for a serially-arranged RMS, considering precedence relations of operations. They formulate an MIP and suggest using an EA to minimize the number of machines needed to meet a prespecified demand. The research is extended by Koren, Wang and Gu (2017). Bensmaine, Dahane and Benyoucef (2013) propose a nondominated sorting genetic algorithm for optimal machine selection in RMS. They bi-objectively aim to minimize the total system costs and the production completion time while assuming full flexible material handling among the deployed machines. Except for Bensmaine et al. (2013), all RMS approaches investigate the design of RMS flowlines, thus limiting the available material handling flexibility to a great extent. EA is mainly used as a heuristic approach.

Uncertainties are considered by integrating machine reliability (Das & Abdul-Kader, 2011; Diallo M., Pierreval H., Quilliot A., 2001; Rafiee et al., 2011; Saeed Jabal Ameli & Arkat, 2008) and demand uncertainty (Pillai & Subbarao, 2008; Tolio & Valente, 2009). Diallo M. et al. (2001) develop a markov chain model to depict the system states of CMS and integrate machine failures. Saeed Jabal Ameli and Arkat (2008) model the breakdown time for each machine following an exponential distribution with a known failure rate. Das and Abdul-Kader (2011) consider exponentially distributed machine failure and repair times while both probabilities are changing over time. The authors model the system's states using a Markovian approach. Rafiee et al. (2011) assume deterministic machine failures and process deterioration. Pillai and Subbarao (2008) consider demand forecasts of several periods to derive robust initial designs of CMS using an MIP and an EA. Tolio and Valente (2009) propose a two-stage mixed-integer stochastic programming approach for the economic design of FMS. In the first stage, current and future production requirements are analyzed and formalized and then used as the stochastic input for the second phase, in which a stochastic MIP is developed to derive economic designs for FMS.

5.2.3. Emerging topics

Emerging topics relating to machine flexibility are *optimization methods* and *restrictions of machine flexibility*. Regarding the *optimization methods*, only IP and MIP models and heuristics are proposed, which we attribute to the combinatorial nature of the capacity decisions relating to machine flexibility. However, the (integer) decisions on the use of resources (e.g., the quantity of different machines) and the (continuous) anticipation of the resulting system performance (e.g., utilization of machines, material flows) can potentially be decomposed. For such problems, Benders' decomposition algorithms have successfully been applied (Heragu & Chen, 1998; Sikora, 2021; Sikora & Weckenborg, 2023). If the objective function only depends on the integer variables (e.g., costs depending on the deployment of resources), combinatorial Benders' Cuts are considered promising. Applying Benders' decomposition approaches is highly encouraged as this applies to manifold capacity decisions in manufacturing system design. Please refer to the seminal article of Codato and Fischetti (2006) for an introduction to the method.

Twofold opportunities arise to consider *restrictions of machine flexibility*. First, only few articles in the review database directly address uncertainty by restricting machine flexibility in static manufacturing system design. The authors address machine reliability (Das & Abdul-Kader, 2011; Diallo M., Pierreval H., Quilliot A., 2001; Rafiee et al., 2011; Saeed Jabal Ameli & Arkat, 2008). However, considering machine reliability in static approaches to manufacturing system design facilitates hedging against failure. To this end, machine failures can already be anticipated in the decisions (e.g., quantity and type of machines and operation-to-machine assignment), and their impact can be estimated. Therefore, the robust design of manufacturing systems is facilitated (Müller, Grunewald & Spengler, 2017; Müller, Grunewald & Spengler, 2018). Second, an opportunity arises in considering the regular downtimes of machines. Besides others, these may result from setups or cleanings and depend on batches, volumes, time, or operation sequences (Scholl, Boysen & Fliedner, 2013; Stefansdottir, Grunow & Akkerman, 2017). The anticipation of these restrictions to machine flexibility may provide additional value to the scientific community and practitioners on manufacturing system design.

5.3. Labor flexibility

5.3.1. Characterization of literature

Analogously to machine flexibility, labor flexibility refers to the range of operations workers can perform within corresponding processing times and the workers' abilities to be assigned and relocated in the manufacturing system. Generally, labor flexibility can only be considered if workers are explicitly addressed. Only 15 out of 144 articles in the review database consider using workers in manufacturing system design. As most of these articles (13 out of 15) consider both machines and workers, they refer to machine flexibility and labor flexibility. However, two articles consider workers as the only available resource and thus neglect machine flexibility (Liu et al., 2013; Vairaktarakis G.L., Cai X., Lee C.-Y., 2002).

In most cases, workers are represented similarly to machines. Labor flexibility is thus predominantly classified by the workers' limitations concerning capacity supply (13 of 15 articles), processing times (15 of 15 articles), and capabilities (15 of 15 articles). Just as machines may be considered substitutes for one another, workers are considered substitutes for machines by several articles (Liu et al., 2013; Vairaktarakis et al., 2002). Relating to the workers' higher creativity and decision-making skills compared to machines, some articles assume the *workers as dual-constrained resources* that need to be paired with suitable machines to execute operations (Mansour, Afefy and Taha, 2022; Rezazadeh et al., 2009; Satoglu and Suresh, 2009). Only one article strictly considers the decision-making skills of workers by assigning separate capabilities to machines and workers (Zhu et al., 2022).

As for machine flexibility, the tradeoff between the extent of maintained labor flexibility and the costs of the systems can be considered to determine an economically beneficial degree of labor flexibility. For workers, *salary costs*, *worker overtime costs*, *hiring and firing costs*, and *training costs* find frequent application (Goli, Tirkolaee and Aydin, 2021; Mahdavi et al., 2010; Mehdizadeh, Daei Niaki and Rahimi, 2016).

5.3.2. Operations Research approaches

Generally speaking, only a few articles consider workers as resources in the design of manufacturing systems, although operations are, to a large extent, executed by human labor in several industries, e.g., the automotive industry (Hottenrott and Grunow, 2019). The *decisions* relating to labor flexibility mainly address the allocation of workers to the system's stations. Frequently, this is accompanied by decisions on the number of used workers or stations.

Articles mainly pursue economic *objectives* in which composite costs comprising the abovementioned components are minimized. Thus, considering the economic aspects of labor is well-established. Only two articles address non-economic objectives. Zhu et al. (2022) aim to minimize the completion time of operations and workers' idle time while considering their decision-making skills cooperating with collaborative robots. Bortolini et al. (2021a) address a social objective in which the authors aim to minimize the overall repetitive movement workers experience by changing auxiliary modules of machines. Using the auxiliary indicator of overall repetitive movements, the approach aims to minimize the ergonomic strain of workers. However, since a maximum tolerable limit has not been taken into account, it cannot guarantee designs feasible in practice.

For the applied exact *optimization methods*, mainly (mixed-)integer programming approaches are proposed. Mahdavi et al. (2010) formulate an IP for the economic design of dynamic CMS while considering workers and machines as dual-constrained resources. Ghotboddini, Rabbani and Rahimian (2011) formulate an MIP while also considering workers as dual-constrained resources. In contrast to Mahdavi et al. (2010), workers are assigned to stations instead to machines. Additionally, Ghotboddini, Rabbani and Rahimian (2011) propose a Bender's decomposition approach to solve the problem in shorter computational time. For heuristic approaches, Satoglu and Suresh (2009) apply a three stage procedure. They first classify products into families according to their demand. Then, they solve the machine grouping problem as a linear integer goal program. Subsequently, workers are assigned to the already formed cells. Zhu et al. (2022) apply a non-dominated sorting genetic algorithm linking the objectives of operational cost minimization and idle time minimization for a manufacturing system consisting of workers and collaborative robots. Deep (2020) proposes a hybrid metaheuristic following the metaheuristic framework of evolutionary algorithms, in which he reduces the acceptance rate of non-improving solutions over the iterations. To this end, he integrates an annealing process.

It should be noted that only one article addresses *uncertainties* relating to labor. Goli, Tirkolaee and Aydin (2021) assume the processing times of workers as triangular fuzzy numbers and thus anticipate the different performances of heterogeneous workers.

5.3.3. Emerging topics

Emerging topics relating to labor flexibility are *collaboration* and *social objectives*. Several articles on labor flexibility consider workers as dual-constrained resources required to operate machines. In recent years, manufacturing system design literature has discussed the optional rather than enforced *collaboration* of multiple resources. Applications may refer to the collaboration of multiple human workers and collaborative robots on an identical task leading to synergies relating to, e.g., lower processing times compared to the individual execution of tasks by either of the resources (Sikora & Weckenborg, 2023; Weckenborg et al., 2020). This idea is in line with hybrid manufacturing, where multiple machines' collaboration may yield a higher performance level than individual machines (cf. Section 2). From the methodological perspective, the collaboration of resources induces additional scheduling characteristics to the design problems, as operations require an allocation in the stations over time. Considering these synergies of collaborating resources offers additional potential and may yield exciting research opportunities for Operations Researchers in manufacturing system design.

Among the articles in the review database, only one article considered a *social objective*. In neighboring literature streams, the consideration of ergonomics in the design of manufacturing systems finds increasing attention (Gunther, Johnson & Peterson, 1983; Otto & Scholl, 2011; Weckenborg, Thies & Spengler, 2022). However, the lack of consideration in the design of manufacturing systems considering flexibility overestimates the systems' quality. It is therefore highly suggested to incorporate human factors to limit labor flexibility to a realistic extent. From a modeling perspective, integrating the complex nature of physical and socio-psychological stresses and the resulting strains may provide exciting opportunities at the intersection of Operations Research and engineering domains.

5.4. Operation flexibility

5.4.1. Characterization of literature

Operation flexibility refers to the considered products and is the degree of freedom they inherently allow to adapt the sequence of executing operations. In the articles in the review database, operation flexibility is considered according to four different approaches, presented in the order of decreasing operation flexibility.

Operation flexibility is unrestricted and *fully available* if no predetermined sequences need to be considered between operations (73 of 144 articles). In this case, operations can be executed in any arbitrary order (Goyal, Jain & Jain, 2012; Pourvaziri et al., 2022; Songore & Songore, 2000). If operation flexibility is restricted, predetermined sequences of operations need to be considered in their execution. Formally, this can be depicted by precedence relations describing the mandatory sequences between tuples of operations. Accordingly, operation flexibility may be restricted by considering the *precedence relations* between operations (25 of 144 articles). In the associated approaches, each operation has known preceding and succeeding operations and can only be executed when all of its predecessors were considered beforehand (Logendran & Sirikrai, 2000; Rahimi, Arkat & Farughi, 2020; Wang & Koren, 2012). The compliance to precedence relations limits the number of feasible sequences of operations and therefore restricts the available operation flexibility. Several articles limit operation flexibility toward a *prespecified set of sequences*, not explicitly considering the precedence relations (11 of 144 articles). Consequently, each product needs to be allocated to one of the prespecified sequences (Campos Sabioni, Daaboul & Le Duigou, 2022; Chung, Wu & Chang, 2011; Solimanpur, Vrat & Shankar, 2004). Finally, operation flexibility may be *unavailable* if operations need to be executed in a fixed and predetermined order (35 of 144 articles). In this approach, the precedence relations for each product are operationalized as a serial arrangement. Consequently, each product can be produced strictly following its prespecified sequence (Kia, 2020; Kia et al., 2014; Wang, Wu & Liu, 2001). Please note that this does not imply that there can only be a predetermined and unique path of products through the stations.

5.4.2. Operations Research approaches

Decisions relating to operation flexibility occur when production sequences are selected to anticipate the short-term execution of production processes. Most articles integrate these *production planning* and *control decisions* to anticipate the operative performance of the manufacturing system design by deciding on a sequence. Moreover, various articles explicitly consider operation flexibility by selecting fixed sequences from a set of prespecified ones (Campos Sabioni, Daaboul & Le Duigou, 2022; Chung, Wu & Chang, 2011; Das & Abdul-Kader, 2011; Das, Lashkari & Sengupta, 2006, 2006; Defersha & Chen, 2006a; Defersha & Hodiya, 2017; Diallo M., Pierreval H., Quilliot A., 2001; Fan & Feng, 2013; Khettabi, Benyoucef & Boutiche, 2021; Lamba et al., 2020; Mohammadi & Forghani, 2014; Rafiee et al., 2011; Saeed Jabal Ameli & Arkat, 2008; Solimanpur, Vrat & Shankar, 2004).

Mainly, economic or performance-oriented *objectives* are pursued. Regarding economic objectives, several studies have focused on minimizing either the total costs of the manufacturing system (Campos Sabioni, Daaboul & Le Duigou, 2022; Defersha & Chen, 2006a; Mohammadi & Forghani, 2014; Rafiee et al., 2011; Solimanpur, Vrat & Shankar, 2004) or the material transport costs (Chung, Wu & Chang, 2011; Defersha & Hodiya, 2017; Saeed Jabal Ameli & Arkat, 2008). In terms of performance-oriented objectives, studies aim to minimize the transport distance (Diallo M., Pierreval H., Quilliot A., 2001; Fan & Feng, 2013; Solimanpur, Vrat & Shankar, 2004). Moreover, two articles consider an ecological objective (Khettabi, Benyoucef & Boutiche, 2021; Lamba et al., 2020). Lamba et al. (2020) integrate electric energy consumption in a compound objective with cost terms. They develop a binary integer program (BIP) and apply an SA. However, the integration of ecological aspects remains superficial as criteria with different units (monetary units (e.g., EUR) and energy units (e.g., kWh)) are considered in a joint objective function. Khettabi, Benyoucef and Boutiche (2021) investigate the sustainable design of RMS by pursuing a multi-objective approach minimizing the total production costs, the total production time, the total amount of green house gasses, and hazardous liquid wastes. A BIP and a non-dominated sorting genetic algorithm are proposed to assess the conflicting objectives. A posteriori, the Technique for Order Reference by Similarity to Ideal Solution (TOPSIS) is applied. Noticeably, each objective considers the material transport distance, indicating the strong link of operation flexibility to the anticipation of *production planning* and *control decisions*.

Regarding *optimization methods*, (mixed-)integer programming models and various heuristic approaches are proposed. Approaches on CMS predominantly decide the production sequence from a set of fixed sequences. In other manufacturing paradigms, production sequences are assumed as fully flexible (FMS), or precedence relations are considered specifically (RMS). Solimanpur, Vrat and Shankar (2004) propose an EA that minimizes investments, processing time, and grouping efficiency of resources. The EA explores the solution space in multiple directions by utilizing several fitness functions with corresponding weights to examine the Pareto-optimal frontier. Chung, Wu and Chang (2011) formulate a BIP to depict the cost-oriented design of CMS and apply a TS algorithm. The TS is extended by mutation operators of an EA to explore the solution space. Mohammadi and Forghani (2014) integrate the decisions about subcontracting into CMS design and propose an EA to derive solutions. Defersha and Hodiya (2017) propose an MIP and an SA that utilizes parallel multiple search paths to reduce computing time. Campos Sabioni, Daaboul and Le Duigou (2022) integrate the design of modular products into the design process of RMS to cope with the increasing demand for mass customization. A BIP and an EA are developed.

Equally to machine flexibility, *uncertainties* with regard to operation flexibility are considered by integrating machine reliability into the approaches (Das & Abdul-Kader, 2011; Das, Lashkari & Sengupta, 2006; Diallo M., Pierreval H., Quilliot A., 2001; Rafiee et al., 2011; Saeed Jabal Ameli & Arkat, 2008). When deciding on an operation sequence for production, the reliability of the machines conducting the operations is highly relevant as machine failures might prevent an efficient production. In this context, machine reliability is especially considered when performance-oriented objectives, e.g. the minimization of the production completion time, are minimized.

5.4.3. Emerging topics

Emerging topics relating to operation flexibility are *product design* and *complications*. As operation flexibility refers to the freedom to adapt the sequence of operations, it is closely interrelated with *product design*. Generally speaking, the Operations Research community has extensively researched various issues in product design. Besides others, these relate to determining a mix of product attributes that attracts customers and increases the corporations‘ profits (Albritton & McMullen, 2007), or trading the reduced production costs of products with higher commonality off against the products‘ reduced desirability by customers (Kim & Chhajed, 2000). Further, the advantages and disadvantages of high product dismantlability in light of market competition are assessed (Wu, 2012). However, these approaches facilitate a supply chain or corporate perspective. Assessing the interrelations between product design and manufacturing system design is desirable. Particularly promising may be the integration of the product design and manufacturing system design decisions. For example, economically better solutions may be found if product design goes into advance to increase the operation flexibility of the considered products and thus facilitates using beneficial operation sequences in the manufacturing system designs (or vice versa). To this end, the precedence relations can link product design generating the potential operation sequences and manufacturing system design using the available operation sequences. First work in this field has been published recently (Battaïa et al., 2018; Campos Sabioni, Daaboul & Le Duigou, 2022). Further, integrating approaches to determine the possible operation sequences into manufacturing system design approaches may provide promising perspectives (Lambert, 2006).

Further, *complications* may affect and adapt the feasible operation sequences. Besides others, they may relate to revisiting products requiring rework by a specific resource, e.g., due to task failure or a varying quality of provided products. Prominently, hazardous operations requiring special handling by the resource are emphasized (Bentaha et al., 2015; Özceylan et al., 2019). An overview of potential complications is provided by Özceylan et al. (2019) on the example of disassembly. However, most of the addressed complications can be transferred to assembly processes and provide research opportunities in manufacturing system design considering operation flexibility.

5.5. Material handling flexibility

5.5.1. Characterization of literature

Material handling flexibility is inherent to the material handling system of manufacturing systems and expresses the possibility of products being transported between resources (stations, machines, and workers) during the manufacturing process. Analogously to operation flexibility, material handling flexibility is considered by three approaches, which will be presented in the order of decreasing material handling flexibility.

Material handling flexibility is *fully available* when each resource can freely be accessed from other resources during the manufacturing process (92 of 144 articles) (Defersha & Chen, 2006a; Mak, Wong & Wang, 2000; Salimpour, Pourvaziri & Azab, 2021). For these approaches, resources usually represent productive units and do not necessarily need to be allocated to precompiled working units. However, if machines or workers are grouped into stations, the material handling between those stations may be restricted to enforce an efficient material flow. Therefore, one limitation of the material handling flexibility is the *serial arrangement* of stations, in which the material flow strictly follows the prespecified order of stations (43 of 144 articles). However, the material flow between the workers or machines within the individual stations is usually not restricted (Huang & Yan, 2020; Kumar A., Jacobson S.H., Sewell E.C., 2000; Solimanpur, Vrat & Shankar, 2005). The most restricted setting is characterized by *disabled material handling between stations* (9 of 144 articles). In these cases, products cannot be transferred between machines or workers of different stations such that the production has to be conducted in individual stations (Arzi, Bukchin & Masin, 2001; Erenay et al., 2015; Solimanpur, Vrat & Shankar, 2004).

As for machine and labor flexibility, the tradeoff between the extent of material handling flexibility and the costs of the systems can be considered to determine an economically beneficial degree of material handling flexibility. The cost-oriented consideration of material handling is conducted via costs for required distances of material handling in which higher costs occur for higher distances (Ah kioon, Bulgak & Bektas, 2009b; Goli, Tirkolaee & Aydin, 2021; Xambre & Vilarinho, 2003). To enable an efficient grouping of resources, material handling costs between stations often induce a higher cost rate than material handling between resources within the same station (Kia et al., 2012; Mansour, Afefy & Taha, 2022; Safaei, Saidi-Mehrabad & Babakhani, 2007).

5.5.2. Operations Research approaches

The *decisions* related to the material handling flexibility are directly linked to the *layout* of the manufacturing system. Therefore, the available resources (by number and type) are assigned to locations, positions, or stations to derive a physical design of the shop floor. The resulting layout consequently prespecifies the available degrees of freedom and the efficiency of material handling during operation. In the decisions on the layout, the flexibility of the resources (i.e., machine flexibility and labor flexibility) maintains high relevance, as their limitations need to be considered in the design of the material handling system to ensure a feasible material flow.

Regarding the *objectives*, approaches incorporating decisions on material handling flexibility mainly pursue performance-oriented objectives and aim to minimize the total material handling distance of the manufacturing system layout. In the context of FMS and RMS, material handling flexibility is restricted as the material transport is predominantly assumed to be conducted along a row of resources or stations containing resources. In this case, the arrangement of resources resembles the single row facility layout problem (SRFLP), in which a known number of facilities with given dimensioning and known material flow quantities among facilities need to be arranged along a row to minimize the weighted sum of the distances between all department pairs (Amaral, 2006). Articles in the review database analogously extend the facility layout problem by considering a double row (Amaral, 2019; Amaral, 2022), multiple rows (Fischer, Fischer & Hungerländer, 2019; Hungerländer & Anjos, 2015), or circular layouts (Potts & Whitehead, 2001) and solve the problem as the part of manufacturing system design. The facility layout problem can additionally be extended to a multi-bay facility layout problem (Chae & Peters, 2006b; Dahlbeck, 2021) or the T-row facility layout problem (Dahlbeck, 2021). For a comprehensive overview of Operations Research methods for facility layout problems, please refer to Anjos and Vieira (2017). In the case of CMS, material handling distances are often implicitly minimized by applying a cost rate to the distances (Chae & Peters, 2006a; Defersha & Hodiya, 2017; Kumar & Singh, 2017, 2018; Yang, Peters & Tu, 2005). The cost rates for intercell transport may be assumed to be higher to incentivize intra-cell transport. When layout decisions are taken together with capacity decisions (e.g., number and type of resources), objectives tend to minimize the manufacturing system design's total costs comprising material handling costs and resource procurement costs.

The *optimization methods* comprise a rich body of exact procedures. Mainly (mixed-)integer programming models. Additionally, various heuristic approaches are proposed, including evolutionary algorithms (Chung, Wu & Chang, 2011; Datta, Amaral & Figueira, 2011; Goli, Tirkolaee & Aydin, 2021; Mak, Wong & Wang, 2000; Mohammadi & Forghani, 2014) and simulated annealing (Baykasoglu, 2003; Chae & Peters, 2006a; Tubaileh & Siam, 2017; Xambre & Vilarinho, 2003; Yang, Peters & Tu, 2005) being proposed the most.

Several approaches aim to optimize different layouts for FMS. If not mentioned explicitly, the approaches minimize the material handling distances of the total material transport. Solimanpur, Vrat and Shankar (2005) examine the design of single-row layout FMS considering the dimensions of the deployed machines. They formulate a BIP and apply an ant colony optimization algorithm. Amaral (2006) develops an MIP for the SRFLP with fewer continuous variables than former MIP approaches. Datta, Amaral and Figueira (2011) propose an EA to solve the SRFLP, which integrates rule-based and random procedures into the population generation. Tubaileh and Siam (2017) develop and apply an SA and an ant colony optimization algorithm to solve the design problem for single and multi-row FMS. Amaral (2019) presents an MIP improving former MIP approaches by integrating valid inequalities and a symmetry-breaking constraint. Amaral (2022) applies a two-step heuristic with an integrated linear programming approach. Hungerländer and Anjos (2015) develop a semidefinite optimization approach for the multi-row facility layout problem. Anjos, Fischer and Hungerländer (2018) reformulate the multi-row facility layout problem into a BIP by cutting out all continuous variables. Additionally, they propose a binary semidefinite optimization model to reduce the computational time to solve the problem. Fischer, Fischer and Hungerländer (2019) propose an MIP for the multi-row facility layout problem and use an enumeration scheme to incorporate investigations on the combinatorial structure of the problem to eliminate solutions. Potts and Whitehead (2001) investigate the impact of a loop on the design of FMS. They decide on the machine-to-station and operation-to-machine assignment to minimize the workload imbalance among stations with a lexicographically subordinate objective to minimize the material handling among stations. An MIP is formulated to solve the problem. Yang, Peters and Tu (2005) investigate the layout of a single-loop FMS and aim to minimize the total material handling costs. They propose an MIP and apply an SA. Chae and Peters (2006a) examine the closed-loop layout for FMS and apply an SA that integrates changes of the rectangular loop structure of the conveyor, resulting in an open field layout. Saravanan and Kumar (2015) investigate the design of loop layout FMS to minimize congestion during material handling.

Approaches for CMS layout are mainly concerned with the cell formation problem. The cell formation problem is associated with grouping resources into stations and assigning products or their respective operations to the formed stations to facilitate an efficient manufacturing process. Thus, decisions about the machine-to-station and product or operation-to-machine assignment are taken. The positioning of stations on the shopfloor can also account for the material handling distance induced by material handling between stations. Mak, Wong and Wang (2000) propose an EA to solve the cell formation problem. They aim to maximize the grouping efficiency of machines. Baykasoglu (2003) proposes a distributed layout approach for CMS while considering additional virtual stations. The objective of the distributed layout is to minimize the material handling distance from each location on the shopfloor to machines of all capabilities. They suggest the use of an SA to solve the problem. Solimanpur, Vrat and Shankar (2004) examine the design of CMS by assigning machines to stations and operations to machines. They pursue a multi-objective approach by minimizing the total dissimilarity of machines assigned to stations, the total material handling costs, the total material handling time, and the total machine purchase costs. A multi-objective IP is formulated and a multi-objective evolutionary algorithm is applied to solve the problem. Mohammadi and Forghani (2014) incorporate the decision on station positioning on the shop floor and decisions on subcontracting into the cell formation problem. They propose an IP to depict the problem and apply an EA to solve it while minimizing the total variable costs of the layout. Mansour, Afefy and Taha (2022) are simultaneously considering machines and workers as resources. They formulate an IP to derive initial layouts that are subsequently detailed by a heuristic procedure. Goyal and Jain (2015) investigate the design of RMS flowlines by deciding on the assignment of machines to stations and operations to machines. They pursue a multi-objective approach and aim to minimize the total system costs while maximizing the RMS design's resource utilization, convertibility, and capability. They apply a multi-objective particle swarm optimization to solve the problem.

Uncertainties in material handling flexibility relate to demand uncertainties and machine failures. Arzi, Bukchin and Masin (2001) examine the design of CMS under lumpy demand. Solimanpur, Vrat and Shankar (2002) apply a transiently chaotic neural network. Egilmez, Süer and Huang (2012) and Egilmez and Süer (2014) investigate the cell formation problem under the assumption of stochastic demand. Chung, Wu and Chang (2011) examine the design of CMS while considering machine breakdowns to minimize the sum of material handling costs and machine breakdown costs. Goli, Tirkolaee and Aydin (2021) consider the cell formation problem under fuzzy processing times while additionally considering workers. Noticeably, uncertainties in the form of demand uncertainties or machine failures are covered in cell formation approaches. However, this does not hold for FMS or RMS design approaches explicitly considering material handling flexibility.

5.5.3. Emerging topics

Emerging topics relating to material handling flexibility are the *material handling systems* and *parts supply*. Regarding the *material handling systems*, their design is yet unconsidered. In existing approaches, material handling is predominantly assessed based on the required travel distances of the associated means of transport. Potentially, the distances may be weighted by a cost factor. However, incorporating decisions on the type and length of conveyors or the type and number of other means of transport is not considered. Therefore, including capacity decisions in consideration of material handling flexibility is highly desired. By explicitly considering the types of transport, the evaluation of novel technologies arising for intralogistics is further facilitated. Recently, autonomous mobile robots gained increasing attention for intralogistics (Fragapane et al., 2021). Including design decisions on material handling systems in manufacturing system design facilitates their assessment.

Regarding *parts supply*, we only find approaches in the review database considering the material flow of the original products. However, the material required for the original products in a convergent material flow is unconsidered. Similarly, the parts originating from disassembling the original product remain unregarded in settings with divergent material flow. As those may consume a significant share of the material flow, their consideration is strongly advised. To this end, integrating the vividly researched domain on warehouse operations (Boysen et al., 2019; Boysen, Koster & Füßler, 2021; Boysen, Koster & Weidinger, 2019) with manufacturing system design provides ample opportunity for Operations Research scientists.

5.6. The impact of basic flexibilities on system flexibilities

As previously introduced, basic flexibility types are inherent to the manufacturing system's resources, material handling systems, and products. Unless restricted by assumptions of the specific setting, they can be assumed as exhaustively available; however, various assumptions motivate restrictions limiting their extent in scientific literature. The basic flexibility types enable the manufacturing systems in two ways, if available. *First*, products can be produced using *different routes* through the manufacturing system during production. Machine and labor flexibility contribute to this via higher capabilities of machines and workers and efficient execution of operations. Operation flexibility allows altering the sequences of operations the considered products require. Material handling flexibility enables the exploitation of these degrees of freedom by ensuring the accessibility of resources. *Second*, the basic flexibility types enable the *system flexibility types*, allowing the manufacturing system to adapt over time. Several articles make assumptions about machine flexibility in dynamic environments as enablers to facilitate system flexibilities specifically. To ensure efficient material transport over time, some articles assume *relocatable machines* (Campos Sabioni, Daaboul & Le Duigou, 2022; Kia et al., 2012; Safaei, Saidi-Mehrabad & Babakhani, 2007). Other articles refer to *(re-)configurable machines*. (*Re*)configuration may refer to a physical change of (auxiliary) modules of machines to adapt their capabilities over time (Khettabi, Benyoucef & Boutiche, 2021; Koren, Wang & Gu, 2017; Youssef & ElMaraghy, 2006). Alternatively, (re-)configuration may relate to adjusting the intensity of the machines' operation without their physical adaptation (Liu, Wang & Zhou, 2019). For machine relocation, *machine relocation costs* or *installation/de-installation costs* may apply (Ah kioon, Bulgak & Bektas, 2009b; Kia, 2020; Saitou, Malpathak & Qvam, 2002). For machine reconfiguration, *machine reconfiguration costs* may take effect (Deep, 2020; Moghaddam et al., 2020; Saxena & Jain, 2012). Analogously to the (re-)configuration of machines, workers' capabilities may be adapted over time by *worker training* (Liu et al., 2013; Rezazadeh et al., 2009; Satoglu & Suresh, 2009). The following sections analyze the four system flexibility types and their relation to the basic flexibility types. As the system flexibilities can only occur in a dynamic environment, only articles with a dynamic setting are investigated to derive insights into the system flexibilities.

5.7. Mix flexibility and product flexibility

5.7.1. Characterization of literature

Mix flexibility relates to the capability of manufacturing systems to respond quickly and economically to variations in the product mix. On the contrary, product flexibility describes the ease with which new products can be added or substituted from the current manufacturing process. While mix flexibility addresses a shift of product volumes within a known portfolio, adding formerly unconsidered products to the portfolio facilitates product flexibility. Mix flexibility is considered in 48 of 144 articles of the review database whereas product flexibility is addressed in 11 of 144 articles.

The differentiation of mix and product flexibility proves difficult when analyzing the design approaches considered in the articles. Both flexibility types are only considered by adapting the manufacturing system to a dynamic and changing demand over time (Bortolini et al., 2021b; Defersha & Chen, 2006a; Wang, Wu & Liu, 2001). The demand is predominantly assumed to be deterministic and only in some articles assumed to be stochastic (Renna & Ambrico, 2015; Safaei, Saidi-Mehrabad & Babakhani, 2007; Safaei et al., 2008). In cases of stochastic demand, however, it is not specified if the dynamic demand changes only account for shifts of volumes between periods and products or incorporate additional and formerly unknown products. Therefore, a clear separation of mix and product flexibility cannot be achieved based on the sole description of the articles.

The separate consideration of product flexibility can only be derived from the motivation of the proposed design approaches. Few articles explicitly mention product changes to motivate their approaches (Haddou Benderbal and Benyoucef, 2019; Kia et al., 2012; Safaei et al., 2008; Tolio and Valente, 2009). Those approaches can be seen to consider product flexibility from a qualitative perspective. However, from an Operations Research perspective, also for these articles mix flexibility and product flexibility cannot be distinguished as they only express an adaptation of the manufacturing system to input data known beforehand.

5.7.2. Operations Research approaches

The *decisions* related to *mix flexibility* are directly linked to the rearrangement of the layout of manufacturing systems. If a dynamic environment is considered, the initially found allocation of resources on the shopfloor might need to be rearranged over time to maintain efficient production. Regarding mix flexibility, rearrangement is mainly required due to changes in dynamic demand. The *decisions* related to *product flexibility* are directly linked to the reconfiguration of already deployed resources. To respond to changes in the product portfolio, the capabilities of available resources might not be enough to cope with the production of entirely new products. Instead of procuring new resources, available resources might be adapted in their functionality. This especially refers to a physical change of (auxiliary) modules of machines to adapt their capabilities over time.

Analogously to the approaches related to material handling flexibility, approaches incorporating *decisions on mix flexibility* pursue performance-oriented *objectives* and aim to minimize the total material handling distance of the manufacturing system layout. As the dynamic environment additionally facilitates the reconfiguration of the layout, the material handling distance is often accounted for cost-oriented by applying a transportation cost rate to combine the material handling costs with reconfiguration costs induced by changing the initial layout in a single cost-oriented objective. Approaches incorporating *decisions on product flexibility* predominately pursue cost-oriented *objectives* and aim to minimize the auxiliary module procurement costs to account for resource configuration decisions.

The *optimization methods* regarding *mix flexibility* comprise (mixed-)integer programming models as exact approaches. Additionally, various heuristic approaches are proposed, predominantly including evolutionary algorithms. Approaches considering the dynamic arrangement of resources on the shopfloor concerning mix flexibility are mainly conducted for CMS. Rezazadeh et al. (2009) investigate the design of dynamic CMS while considering production planning decisions for inventory holding and product subcontracting. An MIP is formulated to depict the problem, and linear programming embedded particle swarm optimization is applied. Mahdavi et al. (2011) integrate the formation of virtual stations for efficient resource assignment and assume machines and workers as dual-constrained resources. They pursue a bi-objective approach and apply fuzzy goal programming. Aghajani et al. (2014) also pursue a multi-objective approach to simultaneously minimize the total system costs, machine underutilization, and system failure rate. An MIP is formulated that integrates ε-constraints to solve the conflicting objectives for small instances. Subsequently, a non-dominated sorting genetic algorithm is applied to solve larger instances. Kumar and Singh (2017) investigate the facility layout design for CMS and aim to minimize the sum of material handling and machine relocation costs using an IP. Lamba et al. (2020) investigate sustainable CMS facility layout designs that consider energy consumption for operation execution. They formulate an MIP and solve the problem by applying a metaheuristic approach based on SA. Salimpour, Pourvaziri and Azab (2021) investigate the layout design for CMS by deciding on the machine-to-station assignment. The machines are additionally assigned to specific positions inside stations to account for intra-station material handling. They aim to bi-objectively minimize the material handling distance and the grouping efficiency of the machine-to-station assignment. An MIP is formulated, and a non-dominated sorting genetic algorithm is suggested to solve the problem. In addition to CMS approaches, Dou, Dai and Meng (2009a) and Dou, Dai and Meng (2009b) examine the design and reconfiguration of a single flowline RMS by deciding upon the assignment and reconfiguration of machines to serially-arranged stations along the flowline. Both articles aim to minimize the total system costs. Dou, Dai and Meng (2009a) formulate a corresponding IP and solve the problem by applying a graph theory-based heuristic. Dou, Dai and Meng (2009b) propose a modified version of the graph theory-based approach.

The *optimization methods* regarding *product flexibility* comprise (mixed-)integer programming models as exact approaches. Additionally, various heuristic approaches are proposed, predominantly including evolutionary algorithms (Ashraf and Hasan, 2018; Campos Sabioni, Daaboul and Le Duigou, 2022; Dou, Li and Su, 2016; Goyal, Jain and Jain, 2012; Khan, 2022; Khettabi, Benyoucef and Boutiche, 2021; Youssef and ElMaraghy, 2006; Youssef and ElMaraghy, 2008). The methods are mainly applied to design RMS as the machines in RMS are assumed to be equipped with auxiliary modules facilitating the reconfiguration process. Goyal, Jain and Jain (2012) consider configuration decisions during the design of RMS flowlines. They derive beneficial initial designs by simultaneously deciding on the number and configuration of machines deployed in the RMS and their assignment to serially-arranged stations, taking precedence relations between operations into account. They pursue a multi-objective approach aiming to minimize purchase costs for machines and maximize the operation range and reconfigurability of the RMS. A non-dominated sorting genetic algorithm is applied to solve the problem. Battaïa, Dolgui and Guschinsky (2017) investigate the design of a rotary RMS under similar conditions by formulating an MIP. Moghaddam, Houshmand and Fatahi Valilai (2018) formulate two IPs, one for the initial configuration and another for the reconfiguration of resources. Ashraf and Hasan (2018) propose a non-dominated sorting genetic algorithm to examine the conflicting objectives of minimizing total costs and maximizing the system's reconfigurability, operation range, and reliability. Haddou Benderbal and Benyoucef (2019) explicitly investigate the adaptability of RMS by introducing new products into the product portfolio. They decide on the configuration of machines and aim to minimize the RMS layout evolution effort by applying a multi-objective SA with an integrated search heuristic. In Bortolini et al. (2021a), machines are reconfigured over time by auxiliary module changes workers conduct. They aim to minimize the required time for material handling and the ergonomic strain of workers expressed by the Occupational Repetitive Actions index and formulate an IP to depict the problem. A normalized normal constraint method is applied to examine the Pareto frontier of the two conflicting objectives. Khan (2022) integrates aspects of product quality into RMS design and formulates an MIP aiming to minimize the total costs, the total operation time, and the scalability of the RMS. A non-dominated sorting genetic algorithm embedded with multiple crossover operators based on simulated annealing is proposed. Tolio and Urgo (2013) investigate the cost-oriented design of flexible transfer lines by formulating an MIP. They decide on the resource selection for an initial configuration and account for reconfiguration costs induced by modifying the initial configuration to adapt to changes in the product mix.

Uncertainties are considered regarding demand and machine reliability. However, both uncertainties are only rarely addressed. Demand uncertainties are considered by modeling the demand in stochastic scenarios in Renna and Ambrico (2015). Machine failures are considered deterministically by Saxena and Jain (2012). Aghajani et al. (2014) consider machine reliability and demand uncertainty simultaneously. Markov chains model machine reliability, and Poisson distributions derive the demand probability.

5.7.3. Emerging topics

Emerging topics relating to mix and product flexibility are the *circular factory* and the *product portfolio.* One promising research perspective facilitated by mix and product flexibility is the *circular factory* to achieve a circular economy. In the circular economy, the forward-directed value chain of materials, components, products, and their distribution and use has to be complemented by a reverse value chain (Brandenburg et al., 2014; Govindan, Soleimani & Kannan, 2015). The forward- and reverse-directed value chain processes in circular factories are provided jointly in a shared facility. Consequently, the production processes with converging and diverging material flows are intertwined. While the network perspective (Alumur et al., 2012) and production planning for the circular economy (Aljuneidi & Bulgak, 2016; Aljuneidi & Bulgak, 2017; Suzanne, Absi & Borodin, 2020) received attention, the design of the integrated manufacturing systems of circular factories lacks consideration.

Against the background of circular factories, the *parts supply* emerging topic addressed under the material handling flexibility (cf. Section 5.5) receives additional perspective. This is, on the one hand, due to the combined nature of parts supply from the warehouse to the resources and the evacuation of recovered parts to the warehouse. On the other hand, the recovered parts can also be fed directly to the converging value stream without a detour to the warehouse, providing rich opportunities for scientists to consider material handling flexibility. Further, the *product design* emerging topic under operation flexibility (cf. Section 5.4) is related, as product dismantlability gains importance in the circular factory. When seminal work on material handling and product design for circular factories has been conducted, circular factories can alternatively use new or recovered parts to adapt to fluctuating quantities of returned products.

Further, mix and product flexibility relate to operation flexibility regarding the *product portfolio*. The methods in the review database cannot distinguish mix flexibility and product flexibility, as they only assume adapting the input data on product demand for a product portfolio known beforehand. Therefore, actual product flexibility is unconsidered by Operations Research approaches related to manufacturing system design. Dedicated scientists in this field may find it challenging to consider unknown future products in manufacturing system design to facilitate the robustness of manufacturing systems against future product portfolio changes. In the automobile industry, where there is uncertainty about future generations of battery technology, this ability also seems to be of particular concern for the advent of circular factories. A starting point to integrating unknown future products into the design of manufacturing systems lies in the methods of revenue management. Within this domain, often sales processes of yet incompletely specified products are examined, whose true nature is only revealed at a later point in time (Gönsch, 2020; Klein et al., 2020; Matzke, Volling & Spengler, 2016). The incorporation of these logics into the design of manufacturing systems represents a promising integration of these disciplines. Approaches determining an advantageous degree of product differentiation can also be helpful in this regard (van den Broeke, Boute & van Mieghem, 2018).

5.8. Volume flexibility and expansion flexibility

5.8.1. Characterization of literature

Volume flexibility describes a manufacturing system's ability to operate economically at different output levels from a short-term perspective and relates to the exploitability of operational degrees of freedom. On the contrary, expansion flexibility describes the ability to operate economically at different output levels from a mid-term perspective and relates to the exploitability of tactical degrees of freedom. While volume flexibility is considered in 23 of 144 articles of the review database, expansion flexibility is considered in 36 of 144 articles.

Volume flexibility is considered when short-term production planning and control decisions are anticipated within the design phase of the manufacturing system and its reconfiguration over time. Several articles within the review database anticipate aspects of production planning and control relating to either external or internal measures of adapting production volume. If external measures are addressed, *backorders*, *outsourcing*, or *subcontracting of specific operations* during the manufacturing process are considered (Mahdavi et al., 2010, 2011; Xue & Offodile, 2020). These measures may reduce the required production capacity of the manufacturing system and thus allow it to operate on a lower output level for a certain period. If internal measures are addressed, *inventory holding* finds attention (Ah kioon, Bulgak & Bektas, 2009b; Kia, 2020; Mahdavi et al., 2010). By shifting production volume between the periods of the considered planning horizon, production capacity utilization can be smoothened across the periods and may affect the decisions on production capacity. Production planning and control aspects are integrated into the manufacturing system design approaches by considering the associated backorder costs, outsourcing costs, subcontracting costs, or inventory holding costs.

Expansion flexibility enables the decision to add resources (stations, machines, and workers) to the manufacturing system or remove them to react to dynamic demand changes. Therefore, the available capacity for production can be adapted. Several articles in the review database consider expansion flexibility. *Stations* can be opened or closed (Dou, Dai & Meng, 2010), *machines* can be purchased or sold (Ah kioon, Bulgak & Bektas, 2009b; Kia, 2020; Saitou, Malpathak & Qvam, 2002), and *workers* can be hired or fired (Deep, 2020; Mahdavi et al., 2010) in particular periods of the planning horizon. As in the previous discussion on volume flexibility, the degrees of freedom provided by expansion flexibility are considered via the associated machine purchase costs, worker hiring and firing costs, and station opening costs.

5.8.2. Operations Research approaches

Decisions relating to volume and expansion flexibility facilitate the manufacturing system to operate economically at different output levels, meet the desired production level, and maintain it in a dynamic environment. Decisions explicitly considering volume flexibility decide in which mode resources are operated to exploit the short-term adaptation of the production quantities to meet changing demand. For machines, the energy level of operation execution can be adapted (Liu, Wang & Zhou, 2019), and for workers, the work intensity can be decided (Fan & Feng, 2013). Unless the decisions relating to volume flexibility, decisions relating to expansion flexibility address the selection of the number and type of resources deployed in the manufacturing system. Thus, the initial capacity decisions are transferred to a dynamic setting and extended by the decisions about selling or procuring additional resources to respond to changing demand. Articles considering either volume or expansion flexibility integrate decisions about production planning, namely outsourcing, subcontracting, and/or inventory holding.

Articles relating to volume and expansion flexibility mainly pursue economic *objectives* to minimize the total costs induced by the manufacturing system, including the costs resulting from the production planning decisions. The remaining performance-oriented objectives (e.g., the material handling distance or the operation completion time) are reformulated to a cost-based consideration to provide a joint consideration within a single objective. In volume flexibility approaches, material handling and operation costs are accounted for, as no additional resource procurement is considered over time. Thus, the short-term indicators are focused. Articles relating to expansion flexibility incorporate decisions about resource procurement over time and therefore relate to mid-term indicators. Generally, considering the economic aspects of volume and expansion flexibility is well-established.

Regarding *optimization methods*, only two articles in the review database can be explicitly linked to volume flexibility, as most dynamic approaches also consider resource procurement. Both consider configuration decisions by adjusting the intensity of operation execution by machines or workers. Liu, Wang and Zhou (2019) investigate virtual CMS's reconfiguration and decide on the machines' energy level during operation execution to adapt the production volume in the sense of volume flexibility. In their approach, machines and workers are assumed as dual-constrained resources. A BIP is formulated, and a priority rule-based heuristic is applied. Fan and Feng (2013) examine CMS design and consider machines and workers as dual-constrained resources. They decide on the work intensity of the operation execution of workers to control the production volume. An MIP is formulated, and a multi-objective evolutionary algorithm is developed to minimize six conflicting objectives.

The *optimization methods* regarding expansion flexibility mainly comprise (mixed-)integer programming models as exact approaches, while few articles also propose dynamic programming (Spicer & Carlo, 2007) or Bender's decomposition (Ghotboddini, Rabbani & Rahimian, 2011) approaches. Evolutionary algorithms are frequently applied (Defersha & Chen, 2006b; Javadian et al., 2011; Kia et al., 2014; Rezaeian et al., 2011; Saitou, Malpathak & Qvam, 2002; Zeidi et al., 2013).

Most approaches concerning expansion flexibility consider the procurement of machines over time. Saitou, Malpathak and Qvam (2002) investigate the design of FMS by applying colored Petri nets and an evolutionary algorithm with integrated dispatching rules. Spicer and Carlo (2007) consider the reconfiguration of scalable RMS. They aim to minimize the total costs for system reconfiguration and apply a heuristic based on dynamic programming to determine the reconfiguration path over time. Defersha and Chen (2006b) and Defersha and Chen (2006a) examine the design of dynamic CMS. Two MIPs that account for various real-world characteristics are formulated, and an evolutionary algorithm is proposed to solve the problem. Similarly, Safaei, Saidi-Mehrabad and Jabal-Ameli (2008) investigate the design of dynamic CMS by formulating an MIP and proposing a hybrid mean field annealing SA algorithm to minimize the total system costs. Wang, Tang and Yung (2009) pursue a multi-objective optimization approach for the design of dynamic CMS. They aim to minimize machine relocation costs and the total material handling distance while maximizing machine utilization. They formulate an MIP and suggest the use of a scatter search approach. Ah kioon, Bulgak and Bektas (2009a) and Ah kioon, Bulgak and Bektas (2009b) extend the design considerations of dynamic CMS with additional decisions on production planning aspects like inventory holding, subcontracting, and production quantity decisions. An MIP is formulated to depict and solve the problem. However, the models can only derive an optimal solution for small instances due to the additional considerations. Kia et al. (2012) examine the design of dynamic CMS and pursue a cost-oriented approach that seeks to minimize the total system costs. They formulate an MIP and solve the problem by applying an SA. The research is extended in Kia et al. (2014) by considering the design of a CMS on multiple floors. The problem is depicted using an MIP and solved by applying a GA. Aljuneidi and Bulgak (2016) integrate remanufacturing processes into the design of CMS by additionally deciding on remanufacturing and recycling decisions. They formulate an MIP to depict and solve the problem. The work is extended in Aljuneidi and Bulgak (2017) by considering disposal operations. The model formulations contain extensive cost considerations but are only assessed for small instances. Xue and Offodile (2020) extend the consideration of dynamic CMS design by considering overtime costs for additional machine capacity. They formulate an MIP to depict the problem and apply an SA to solve the problem.

Only two contributions investigate capacity-related decisions concerning stations. They evaluate incremental CMS, in which resources are initially organized in job shops and are transitioned to a CMS over time. Rezaeian et al. (2011) determine the station opening over time by formulating an MIP and applying a hybrid approach based on neural networks and an evolutionary algorithm. Zeidi et al. (2013) propose an MIP and suggest using a multi-objective approach based on an evolutionary algorithm and an artificial neural network. Both approaches aim to minimize material handling costs during production.

Only one article considers *uncertainties*. Safaei et al. (2008) extend their previous research (Safaei, Saidi-Mehrabad and Jabal-Ameli, 2008) by assuming a fuzzy product demand.

5.8.3. Emerging topics

Emerging topics relating to volume and expansion flexibility are *urban production* and *production ramp-up and ramp-down*. In the face of continuing urbanization trends worldwide, *urban production* can be a promising concept to cope with the scarce availability of land in urban areas. Vertical dispersion of facilities is proposed in urban production to use the restricted space efficiently. To facilitate the design of manufacturing systems in scarce space using Operations Research, first, the dimensions of resources of the manufacturing system must be recognized in the decisions on capacity, layout, and configuration (Javadi et al., 2013). Second, the interdependencies of facilities in multiple facility levels need to be addressed (Kia et al., 2014). Third, the material handling system requires particular attention in vertically dispersed systems. In the articles in our review database, material handling is predominantly anticipated via the (monetarized) required transport distances between the system's resources to comply with production planning. A dedicated design of the material handling system, i.e., incorporating decisions on the type and length of conveyors or the type and number of vehicles, is yet unconsidered. For vertically dispersed manufacturing systems in scarce space, the explicit consideration of design decisions for the material handling system may be essential. Please note that the general idea of urban production relates to multi-floor (or multi-story, synonymously) layout problems addressed early in literature (Kaku, Thompson & Baybars, 1988; Neghabat, 1974). Against the recent context, however, the field of urban production provides promising research perspectives for Operations Research scientists. A review of articles on multi-floor layouts published in other venues is provided by Ahmadi, Pishvaee and Akbari Jokar (2017), which may serve as a starting point for promising research in this direction.

Another promising domain relates to *production ramp-up and ramp-down*. The general idea of the manufacturing systems addressed in this review is to maintain the 'right' level of flexibility to efficiently adapt to anticipated changes in demand. Typically, production ramp-up phases are faced between the end of product development to reach full capacity (Terwiesch & Bohn, 2001). Please also refer to the vital role of product development introduced regarding operation flexibility in Section 5.4. For the manufacturing paradigms addressed in this review, such ramp-up phases are aimed to be avoided by maintaining flexibility. Few articles in the review database refer to the expenses coinciding with necessary adaptations to facilitate the production of new products (Hottenrott, Schiffer & Grunow, 2023; Huang, Wang & Yan, 2019; Spicer & Carlo, 2007). However, ramp-up and ramp-down phases not only refer to the transition between products (or product generations) but also to initially bringing up the production system to full operation after it has been designed and built (Doltsinis, Ratchev & Lohse, 2013). However, based on the latter understanding, no article in the review database addresses the efficient launch of the manufacturing system. However, as manufacturing systems maintaining a higher degree of flexibility may suffer from a less efficient ramp-up accompanied by more complications due to higher system complexity compared to more dedicated and efficient alternatives, this aspect requires urgent consideration. Again, please note the crucial link between product development creating prerequisites for efficient production (Carrillo & Franza, 2006).

6. Conclusion

This paper surveys how Operations Research methods are applied to the design of manufacturing systems considering flexibility. In the established literature, multiple manufacturing paradigms are researched independently. A classification scheme is developed to unite the literature of multiple streams relating to flexibility in manufacturing system design. A systematic search and screening procedure identifies one hundred forty-four articles published in this millennium and relevant to the field.

From their analysis, one observes that many methods from Operations Research are applied to tackle challenges in consideration of flexibility in manufacturing system design. Predominantly, mixed-integer programming approaches and evolutionary algorithms are used. Traditionally, performance-oriented (e.g., maximization of resource utilization or minimization of transport distances) and economic objectives (e.g., minimization of costs or maximization of profit) are considered. The majority of articles consider static time and deterministic problem settings. While machine flexibility is exhaustively considered, the particular aspects of labor flexibility are less addressed. Most articles consider a combination of (static) basic flexibility types, while (dynamic) system flexibilities receive less attention. Layout decisions are taken in most articles, partly in combination with superordinate capacity or subordinate configuration decisions. Decisions on production planning and control are frequently incorporated into the design approaches to anticipate the systems' operational performance.

The domain provides splendid research perspectives for future manufacturing system design. First, existing literature nearly exclusively addresses performance-oriented or economic aspects of manufacturing system design. Future research is suggested to increasingly incorporate ecological and social indicators of manufacturing systems into design considerations. Second, the product development domain proves an important collaborator for manufacturing system design, providing crucial prerequisites for taking advantage of flexibility in the manufacturing system subsequently. Consequently, product development and manufacturing system design should increasingly be tackled jointly. Third, the impact of the material handling systems associated with the manufacturing facilities is mainly anticipated using (weighted) travel distances. Its explicit consideration within the design decisions is neglected.

The described research perspectives may drive relevant societal change. The circular production of goods in circular factories is seen as particularly relevant and may facilitate an ecologically oriented industry by integrating the reverse stages of the value chain into traditionally forward-oriented factories. The intertwined nature of material flow and the more difficult-to-forecast volume of returning products and their condition open ample opportunities for Operations Research. Similarly, the vertical production spanning multiple levels of a factory contributes to establishing factories close to employees' residences and keeping them in employment. In this domain, the realm of Operations Research can contribute significantly by developing state-of-the-art methods and providing decision support to industrial practitioners.

Declarations of Competing Interests

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