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RESEARCH ARTICLE

Classified AGV Material Flow and Layout Data Set for Multidisciplinary Investigation

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ABSTRACT Automated Guided Vehicles (AGV) are increasingly used in industry to automate material flow tasks. To efficiently operate systems of AGVs, researchers have proposed many different planning and control methods, e.g., for scheduling, dispatching, and routing. The performance of these methods depends on the characteristics of the system, such as transport distances and station operation frequencies. Even though these characteristics strongly influence the algorithms, no classified collection of layout data was found based on a scientific literature review. In this paper, a data set of 72 material flow and layout compositions from the scientific literature (42) and German industry (30) is presented. Each composition in the data set consists of a transport matrix and a distance matrix. To classify the compositions, a holistic taxonomy was established based on distinguishing criteria for material flow and layout compositions known from the scientific literature. The compositions were classified according to the taxonomy. An analysis of the station operation frequency and transport distance distribution data reveals typical characteristics of the compositions as well as variations between the classified compositions. The aim of this data set is to allow benchmarking of planning and control methods, thus increasing the transparency and traceability of scientific work. Furthermore, the analysis of the layouts and their taxonomy allows to compare the methods of different disciplines. By providing standardized, machine readable formats, automatic testing and optimization will be possible.

INDEX TERMS AGV, AMR, automated guided vehicle, autonomous mobile robot, automated material flow, distance matrix, intralogistics layout, logistics data set, transport layout, transport matrix.

I. INTRODUCTION

Automated Guided Vehicles (AGVs) and Autonomous Mobile Robots (AMRs) increasingly perform intralogistics processes. However, planning and designing such a system requires a great deal of information about the intended application. In most cases, it is not possible to provide general statements about e.g. the number of vehicles required, without specifically modeling the layout and a simulation. The minimum information required to model the material flow and layout is the number of stations, the transport distance relationship, and the transport frequency relationship between them.

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A. MOTIVATION

To validate new methods in science, a benchmark is available in the ideal case. In many cases, the data used in existing benchmark studies is not publicly available. Therefore, a scientifically well-founded comparison between existing and new methods cannot be carried out. Transparency and traceability are reduced when the data basis is not available. With the transparent and consistent data set described here, it will be possible to conduct various investigations in the planning and control of AGVs. The analysis of the layouts and their taxonomy allows to compare methods of different disciplines based on layout topologies, flow path orientations, and task structures. In order to validate new methods on corresponding material flow and layout classes in future studies, a taxonomy for the classification of material flow and layout compositions is required. The literature already covers aspects such as layout topologies, flow path orientations, and task structures [1], [2], [3], [4], [5], [6]. However, a holistic taxonomy for classification that takes into account all the distinguishing criteria identified was not found in scientific literature.

B. METHODOLOGY

At the beginning of the data set compilation, a literature review was conducted to investigate how a material flow system using AGVs can be described. Furthermore, a literature review of related studies in the field of planning and control of AGVs was carried out to identify the data on which the scientific studies were based. It was found that the most important information to describe a material flow system using AGVs is the transport distances and the transport frequencies. Based on this finding, the data of the individual material flow systems were named material flow and layout compositions, where material flow describes the transport frequencies and layout describes the distance relationships between transport stations. Taking a closer look at the possible modeling types of material flow systems (according to [7]), the transport matrix and distance matrix have emerged as suitable modeling types for providing material flow and layout compositions. On the one hand, these can be used for automated experiments and simulations, and on the other hand, based on the actual data, they can always be extracted by an analysis of the available data or, given the matrix form, be adopted. The applied analysis methods and data acquisition methods are described in III-C and III-D. In order to classify the collected material flow and layout compositions, a literature review was conducted to determine what distinguishing characteristics material flow and layout compositions may have.

C. CONTRIBUTIONS

The data set described in this paper contains 42 material flow and layout compositions from examples in the literature, as well as 30 further data collected from the German industry. Each composition consists of several transport matrices, a distance matrix, an empty run matrix, a station list, and a job list. As a benchmark for minimizing required empty runs in a material flow and layout composition, an empty run matrix was generated for each composition according to [7], showing the minimum number of empty runs needed. All data acquisition and treatment methods for the determination of the transport matrices, the distance matrix, and the job list are described in detail in this paper.

A taxonomy is presented that can be used to classify material flow and layout compositions based on layout topology, flow path orientation, and task structure. Based on the taxonomy, the data are classified into 25 classes. In addition, the applied data acquisition and treatment methods were transparently listed for each composition. An analysis of the data on the station operation frequency and the distribution of transport distance shows typical quantitative indicators for the composition as well as the relationships between the taxonomy criteria. The collected material flow and layout compositions were analyzed according to the quantitative indicators of transport distance and station operation frequency. By comparing the indicators, relationships between the taxonomy criteria were revealed.

Accordingly, the remainder of the paper is structured as follows. In the following chapter, six research topics are presented that benefit from the use of such a material flow and layout data set. In the third chapter, data acquisition and treatment methods as well as the taxonomy criteria are presented. In the fourth chapter, the material flow and layout compositions of this data set are described in detail and classified in tabular form based on the taxonomy introduced in chapter three. In addition, the methods used to acquire and treat the data are contrasted with the corresponding material flow and layout compositions in the appendix of this paper.

II. RELATED WORK

This section illustrates, through the variety of research areas in AGV and AMR planning and control, the potential benefits of the development and publication of the data set described in this paper. The 42 cited publications in the literature review by [8], as well as other scientific studies presented in this section, use similar data as a basis. It is often found that the data on which the studies are based are reproducible either partly or not at all. Reference [8] defined research topics in the strategic, tactical, and operational areas for AGVs and AMRs in a review paper and classified published papers between 2006 and 2020. It was found that at least 42 of the 130 classified scientific studies are based on data such as transport times, transport distances, or job lists. Additional scientific studies based on such data are presented below. For this work, six research areas were defined, inspired mainly by [8], in addition to other literature.

A. LAYOUT TOPOLOGIES AND FLOW PATH ORIENTATION OPTIMIZATION

Initial studies of flow path orientation have already been conducted by [1] and [2]. References [9] and [5] introduced bidirectional flow path orientation and investigated mixed directional flow path orientations, which enabled a higher throughput of the overall system for specific layouts. Furthermore, [2], [9], and [4] investigated a tandem layout topology. These investigations were authoritative for the various subsequent flow path orientations and layout topologies. A taxonomy of these flow path orientations and layout topologies can be found in section III-A. Recent works, such as [10] and [11] are based on the criteria mentioned above. Reference [10] present further differentiation criteria of layouts and path topologies. For layout topologies, they distinguish between two tier and single tier layouts to investigate the performance of an AGV based sorting system, whereas [11] investigate single and multiloop topologies for the design of container terminal operations.

B. LAYOUT AND MATERIAL FLOW PLANNING

When it comes to planning the layout and material flow in a facility, data about the current, planned, or predicted material flow intensity between different stations is important as well. Reference [12] give an overview of loop based facility planning and material handling decisions for material handling equipment like AGVs. They refer to aspects of facility design like sequencing stations and locating production cells, the design, including the material handling system (layout topology), and operational issues such as home locations of idle vehicles and the avoidance of blocking and congestion. An approach to optimally locating workstations in a tandem AGV system by [13] is formalized as a mixed integer programming formulation. Reference [14] presents an integrated genetic approach to the simultaneous design of both the layout and the material handling system in a facility.

C. CHARGING AND OPERATING STRATEGIES

Charging and operating strategies are summarized in the review paper by [8]. They are also reported by [15]. The paper presents a charging strategy designed to smooth the utilization of charging systems over the entire operating period. Reference [16] investigated and compared two charging strategies for improving utilization using real layout compositions. With the conceptualization of a dual energy storage system, another charging strategy was presented in a paper, which refers to the optimization of the energy storage design of AGVs in terms of energy related size. In that case, knowledge about the transport layout as well as their transport orders is necessary for the design and the functional validation of the energy storage system [17].

D. TASK ALLOCATION PROBLEM

The task allocation problem is divided by [8] into the two research areas of scheduling and dispatching. 34% of the classified literature covers these two research areas, which can thus be considered important research topics in the field of planning and control of AGVs. Reference [18] investigated whether applying multi objective generic algorithms to multi-objective scheduling problems enhances the quality of the solution, minimizes the computation time, and maximizes the effectiveness. The study is based on a transport layout, given distances, and order frequencies. Furthermore, [19] studied decentralized task allocation considering energy constraints in their paper, which is a multidisciplinary study based on a transport layout. Based on the same layout composition, a decentralized task allocation considering route constraints was investigated in [20].

E. FLEET SIZING

Planning AGV systems (AGVS) involves, among other things, determining the number of vehicles based on influencing factors, such as transport frequency, distances between stations, and vehicle specifications. Reference [21] developed a discrete simulation model to find the minimum number of AGVs to enable the manufacturing distribution. Reference [22] used a simulation model to investigate the optimal fleet size, considering charging strategies in a specific transport layout. Furthermore, studies can be found in which the vehicle loading capacity is varied. Examples are provided by [23] and [24]. Reference [23] studied the maintenance strategies for multi-load AGVs. The number of vehicles as well as the vehicle capacity were varied. This study was also based on transport distances, which were given in the form of a graph with bidirectional flow path orientation. Regarding multiple load AGVS, [24] presented a mathematical model for configuring a multiple load AGVS for tandem layout topologies based on a given transport layout.

F. ROUTING AND PATH PLANNING

Reference [25] described an algorithm to find the optimal number of vehicles considering conflict-free routing in flexible transport layouts. Six different transport layouts and an exemplary time matrix were used as data to validate this method. Reference [26] presented a method to optimize the coordination of a fleet of AGVs traveling on predefined transport layouts. Reference [27] described different methods for path planning. It is important to emphasize that layout compositions are required as a basis for applying the methods. Studies on dynamic or consistent routing, where the transport frequency relation between stations varies as described in [28] and [29], use both transport frequency relations (cf. customer-based graph in [29]), as well as transport distance relations (cf. road network-based graph in [29]).

III. METHODS

This chapter begins with a taxonomy of material flow and layout compositions and then describes the methods applied for data acquisition, the subsequent data treatment.

A. MATERIAL FLOW AND LAYOUT COMPOSITION TAXONOMY

In this section, a taxonomy of material flow and layout compositions according to flow path orientation, layout topology, and task structure is presented. This allows for a comparison of the quality of the methods to be investigated on the basis of corresponding classes.

1) FLOW PATH ORIENTATION

The flow path orientation defines the allowed direction of movement of the respective flow path specified in the layout. Based on [3], the orientation of the flow paths can be distinguished as follows:

- unidirectional flow path
- bidirectional flow path
- mixed directional flow path

A layout essentially consists of nodes and edges, where nodes can also be stations or junctions. A flow path starts with a node and ends with another node. In a unidirectional flow path layout, all flow paths are limited to one direction. In a bidirectional flow path layout, however, all flow paths can be used in both directions. Combinations of both flow path types in one layout are referred to as mixed flow path layouts.

2) LAYOUT TOPOLOGY

The layout topology describes the 2D arrangement of the stations and the structure of the routes in the layout. Singleloop, multiloop, tandem, and segmented topologies are distinguished. Singleloop has no branches and can have any number of stations. The stations are arranged in a ring structure. If a layout has at least one junction or at least three stations with bidirectional flow paths, it is classified as a multiloop topology.

More complex layouts with a larger number of stations and flow paths can also be described by several linked singleloop systems. These layouts are classified as tandem topologies. Such a layout contains at least two singleloops linked by at least one transfer station. Alternatively, more complex layouts can be described by several linked multiloop systems. These layouts are assigned to the segmented topology. Such a layout contains at least two multiloops connected by at least one transfer station (cf. [3], [4], [30]). The basic idea of split topologies is that they can achieve higher robustness, higher throughput, and higher flexibility in terms of extensibility (cf. [2], [3], [9]).

3) TASK STRUCTURE

A task structure describes the general transport request relationship between sources and sinks. The left digit 1 or m describes the number of sources and the right digit next to the colon with 1 or n is the number of sinks in the system. Based on [3], a task structure can be split into the four following listed categories:

- $(1 : 1)$
- $(1 : n)$
- $(m : 1)$
- $(m : n)$

In a $(1 : 1)$ task structure, there are exactly one source and one sink in the system. This is the case, for example, for a shuttle operation between one source and one sink. The $(1 : n)$ task structure describes a task structure with one source and n sinks. This occurs, for example, in the supply of materials to production lines by route trains (cf. Literature02 based on [21]). In contrast, an $m : 1$ task structure describes a system with one sink and m sources. An example may be a waste disposal system where waste is generated at m sources and transported to a central disposal point, the one sink. The last case is the $m : n$ task structure. It describes systems with at least two sources and at least two sinks and is most common in AGVS (cf. Tables 5 and 6). Table 2 shows the possible combinations between the layout topologies and the task structures.

The combination of a multiloop topology with a $1 : 1$ task structure is not possible, since a multiloop topology is defined by more than two stations. Otherwise, it is a singleloop topology without any outgoing paths to additional sources or sinks.

B. REPRESENTATION OF MATERIAL FLOW AND LAYOUT COMPOSITIONS IN MODELS

In order to identify a suitable representation of the data, the possible ways of modeling material flow and layout compositions in literature were considered and presented below, sorted by decreasing information density. For transport layouts, there is the scaled plan as a modeling type. This is the modeling variant with the highest information density. It contains information about the actual transport routes, the coordinates of the stations, as well as possible dwell points, flow path orientation, and further information about the system periphery, like the position and orientation of obstacles. The next abstraction level is a node-edge graph [7]. Information about the actual transport routes and the coordinates of the stations are represented, as in the scaled plan, only information on the periphery is lost. Through the connectivity in directed graphs, unidirectional as well as bidirectional flow path oriented transport routes can be represented. The next abstraction level is a simplified node-edge graph. It is a visual representation of the transport distance or frequency between the stations. The loss of information on the actual routes of the vehicles can be considered in form of edge weights [7]. The stations can be arranged in the same way as in the real layout, thus keeping the information on the actual spacial relation between each other (cf. [29]). This information content can also be represented as a matrix. The matrix contains only the distance relationship (distance matrix) or the transport frequency relationship (transport matrix) between all stations in the layout [7].

During the collection of material flow and layout compositions, it was noticed that the data was not in a uniform format. Due to the lack of information in most cases, the matrix was chosen as the form of representation. The matrix format is suitable for automated data processing, as it inherently possesses machine-readability and no conversion is needed which would be the case for scaled plan modeling.

C. DATA ACQUISITION METHODS FOR TRANSPORT MATRIX

If the transport orders are not specified as a transport matrix or on an hourly basis, the following methods were used:

- Case: Job sequences
  In some layouts, only job sequences were specified. These occurred, for example, in systems with route trains for supplying production lines. A given job sequence followed a $1 : n$ relationship, with 1 source and n sinks. From a job sequence $(Q \rightarrow S_1 \rightarrow S_2 \rightarrow \ldots \rightarrow S_n)$, single trips were derived, all originating from the single source Q for the job sequence. For a given job sequence $(Q \rightarrow S_1 \rightarrow S_2 \rightarrow \ldots \rightarrow S_n \rightarrow Q)$ that ends at the same Q as started, the last job $(S_n \rightarrow Q)$ is not considered for the transport matrix. These examples

TABLE 1. Classification of layout topologies and flow path orientations. S_n describes stations. Double circled stations are transfer stations. Different lines describe different subsystems. Own illustration based on [1], [2], [3], [4], [5], and [6].

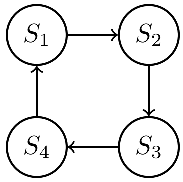
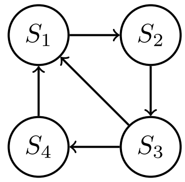
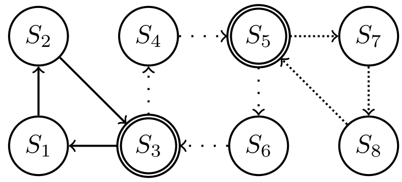
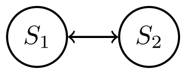
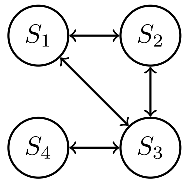
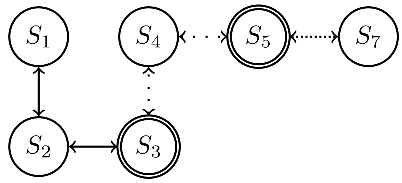
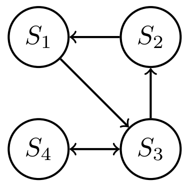
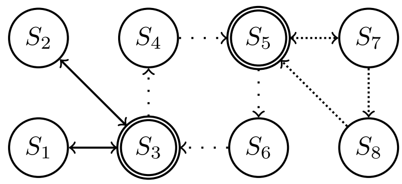
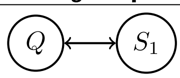
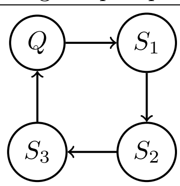
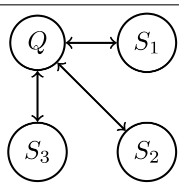
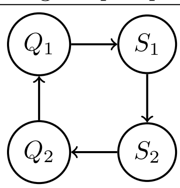
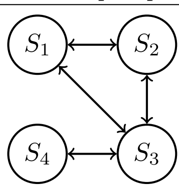
	Singleloop	Multiloop	Tandem
Unidirectional	 Unidirectional Singleloop Topology	 Unidirectional Multiloop Topology	 Unidirectional Tandem Topology
Bidirectional	 Bidirectional Singleloop Topology	 Bidirectional Multiloop Topology	 Bidirectional Tandem Topology
Mixed Directional	N/A	 Mixed Directional Multiloop Topology	 Mixed Directional Tandem Topology

TABLE 2. Possible task structures based on layout topologies. Station denoted by a Q describes a source, S a sink.

	Singleloop	Multiloop
1:1	 1:1 Singleloop Topology	N/A
1:n or m:1	 1:n Singleloop Topology	 1:n Multiloop Topology
m:n	 m:n Singleloop Topology	 m:n Multiloop Topology

of job sequences both result in the job list $J = \{(Q \rightarrow S_1), (Q \rightarrow S_2), \ldots, (Q \rightarrow S_n)\}$. If there were multiple job sequences for a source or an additional source, the job list was expanded accordingly.

- Case: Job list
  If a job list was the basis after data collection, a matrix was derived from the transport order relationships, which correspond to the transport matrix.
- Case: Not normalized period
  If transport data are given based on a time interval $t \neq 1h$, the transport data have been normalized to $t = 1h$.

D. DATA ACQUISITION METHODS FOR DISTANCE MATRIX

In order to use data of a material flow for the data set described here, specification of the transport matrix as well as a description of the station distribution, e.g. with a distance matrix, a time matrix, or a scaled layout plan, are necessary at least. Alternatively to the scaled layout plan, the specification of station coordinates or a graph is sufficient. If the description of the station distribution is not in a distance matrix format, a distance matrix was determined from the given data using the following methods:

- Case: Incomplete distance matrix
  Stations, between which no transport orders are executed, were missing. If missing distances could be determined from a graph or a scaled plan, this was done. In all other cases, no distance relation is set. For machine readability, $d_{mn} = -1$ is used.
- Case: Time matrix
  If a time matrix was given instead of the distance matrix,

an average transport velocity of $V_{\text{avg}} = 1m/s$ was assumed, based on the safe collaboration velocity of AGVs [31]. The multiplication of the time matrix by the scalar quantity of the average velocity V_{avg} results in the distance matrix [32].

- Case: Coordinates
  If coordinates of the stations are given and no more information about routes is available, we used the Manhattan distance method, based on [7]. The Manhattan distance method determines the distance d_{mn} considering only rectangular route trajectories. Reference [33] uses this method for distance determination of AGVs in a warehouse environment. The Manhattan distance between the stations $x, y \in \mathbb{R}^2$ can be described mathematically as $d_{mn} = |x_1 - y_1| + |x_2 - y_2|$, where 1 and 2 are the respective coordinates of the stations.
- Case: Scaled layout plan
  If only a scaled layout plan was given, a coordinate system was placed on the layout and the coordinates of the stations were determined. If information about the routes is known or can be seen from the layout, the distances are determined based on the scaled lengths. Flow path orientation is also taken into account. If no flow path information is available, the Manhattan method is used as an approximation of the distances between two stations (cf. case: coordinates) [7], [33].
- Case: Graph
  A graph contains all stations and their distance relations. In most cases, flow path and nodes are also specified and taken into account when determining the distance. If the distance matrix is based on a graph, the shortest possible path considering the given flow path and its orientation is determined using Dijkstra's algorithm according to [7].

E. DATA TREATMENT METHODS

1) EMPTY RUN MATRIX GENERATION

The empty run matrix results from the need for transports or from the supply of outgoing transport jobs at the stations. For transport systems that use load carriers or vehicles, empty runs are required to fulfill the demand for vehicles or load carriers. The empty runs for the data set described in this paper are determined by minimizing the distances of all empty runs according to [7]. Mathematically, this can be described in simplified terms by the following minimization equation of the total transport distance T:

$$T = \sum_{m=1}^{N} \sum_{n=1}^{N} \lambda_{mn} \cdot d_{mn} \tag{1}$$

$$\min_{\boldsymbol{\lambda} \in \mathbb{R}_+^N \setminus \{0\}} \quad T(\boldsymbol{\lambda})$$

$$\text{s.t.} \quad \sum_{n=1}^{N} (\lambda_{in} - \lambda_{ni}) = 0, \quad i \in \{1, \ldots, N\} \tag{2}$$

TABLE 3. File naming and their referenced chapters.

Filename	Referenced chapter: data description	Referenced chapter: data aquisition and threatment
[LayoutID]_Transportmatrix.csv	IV-A	III-C
[LayoutID]_Distancematrix.csv	IV-B	III-D
[LayoutID]_Stationlist.csv	IV-C	N/A
[LayoutID]_Emptyrunmatrix.csv	IV-D	III-E1
[LayoutID]_Totaltransportmatrix.csv	IV-E	N/A
[LayoutID]_Joblist.csv	IV-F	III-E2

λ describes the frequency of empty runs between stations m and n, where d is the distance between stations m and n and N is the number of stations in the transport layout.

2) JOB LIST GENERATION

A transport job describes a set of equal transport orders and its frequency. The relationship between job and order is further described in section IV-F. The job list is a clearly structured and more easily processable form of provisioning transport jobs. The job list is automatically generated using the total transport matrix, which already includes the empty run matrix. During generation, all cells of the total transport matrix are created as one transport job and the frequency is adopted as an attribute. Then, all transport jobs with a frequency of $f = 0$ are filtered out.

IV. DATA DESCRIPTION

In this section, the data of the data set is described in detail. The material flow data set includes 72 specific material flow and layout compositions, which are stored in several comma separated values (.csv) files. The following Table 3 summarizes all documents of each material flow and layout composition, which are described in detail afterwards.

The contents within the listed files start after a header line, and for matrices after a header column. The matrices are always square, i.e. the number of rows is equal to the number of columns (cf. section IV-A).

A. TRANSPORT MATRIX

The transport matrix A_T describes the frequency of transports between all stations normalized to a time period. The first column shows the respective sources and the first row the respective sinks of a transport order. In the literature, the frequency is typically normalized to one hour and can refer either to specific transport trips or to material transports. If compositions are considered where several conveyor units are transported at the same time, normalize to the number of necessary transport trips to determine the transport jobs. For

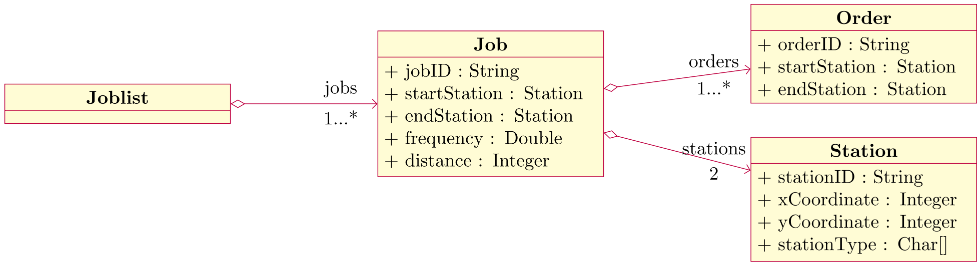


FIGURE 1. UML diagram to illustrate the relationships between job, order, and station.

the main diagonal $\lambda_{mn} = 0, \forall\, n = m$ is valid.

$$A_\mathrm{T} = \begin{vmatrix} From/To & S_1 & S_2 & \dots & S_\mathrm{n} \\ S_1 & 0 & \lambda_{12} & \dots & \lambda_{1\mathrm{n}} \\ S_2 & \lambda_{21} & 0 & \dots & \lambda_{2\mathrm{n}} \\ \dots & \dots & \dots & \dots & \dots \\ S_\mathrm{m} & \lambda_{\mathrm{m}1} & \lambda_{\mathrm{m}2} & \dots & \lambda_{\mathrm{mn}} \end{vmatrix}$$

B. DISTANCE MATRIX

The distance matrix A_D contains the transport distances within a layout. The first column shows the respective sources and the first row the respective sinks of a transport job. The distance matrix for the description of transport distances d is typically given in meters in an intralogistics environment. As for the transport matrix, we assume that $d_{mn} = 0, \forall\, n = m$ applies to the main diagonal.

$$A_\mathrm{D} = \begin{vmatrix} From/To & S_1 & S_2 & \dots & S_\mathrm{n} \\ S_1 & 0 & d_{12} & \dots & d_{1\mathrm{n}} \\ S_2 & d_{21} & 0 & \dots & d_{2\mathrm{n}} \\ \dots & \dots & \dots & \dots & \dots \\ S_\mathrm{m} & d_{\mathrm{m}1} & d_{\mathrm{m}2} & \dots & d_{\mathrm{mn}} \end{vmatrix}$$

C. STATION LIST

The station list is optional and not specified in each composition, but includes at least a column listing all "Station IDs", as well as all "Origin station IDs" to link to the naming in the original literature. Optionally, coordinates are available in meters in some files. Furthermore, information about the station type is available. This includes the types of sink and source, which were determined by the demand and excess of the respective stations from A_T. Each station can also contain a combination of several types. An example of a station list is shown below:

TABLE 4. Sample station list with specification of optional coordinates and functions (*Q*: source, *S*: sink).

Station ID	Coordinates		Type	Origin Station ID
	x in [m]	y in [m]	Q, S	
A	x_1	y_1	Q, S	S_1
B	x_2	y_2	Q, S	S_2
C	x_n	y_n	S	S_n

D. EMPTY RUN MATRIX

The empty run matrix A_TE is similar to a transport matrix (cf. section IV-A), but only contains the empty runs based on a given transport matrix. The empty run matrices are determined according to a method, which is described in section III-E1.

E. TOTAL TRANSPORT MATRIX

The total transport matrix A_TT is also similar to a transport matrix (cf. Section IV-A). It is the sum of the transport matrix A_T and the empty run matrix A_TE and can be mathematically represented as follows:

$$A_\mathrm{TT} = A_\mathrm{T} + A_\mathrm{TE}$$

By determining the empty run matrix based on the transport matrix, the sum of all incoming transport orders per station matches the sum of all outgoing transport orders of the same station. This corresponds to the constraint from (2).

F. JOB LIST

Finally, a job list is specified in a file named [LayoutID]_Joblist.csv. A transport job T_j describes a set of similar transport orders and is characterized by the properties of the transport orders and the frequency of occurrence. The UML diagram in Fig. 1 shows the relationship between job, station, and order, with a job being defined as a transport between exactly two stations in this data set. The job list is normalized to one hour. This allows to generate transport orders for various examinations. In addition, frequency distributions can be derived from the job list, for example, the frequency of specific transport distances or the frequency of outgoing or incoming transport orders of the respective stations.

V. DATA ANALYSIS

A. MATERIAL FLOW AND LAYOUT CLASSIFICATION AND OVERVIEW

The compositions of the data set are classified in Tables 5 and 6 based on the taxonomy presented in Section III-A. Fields marked with dots (•) apply according to the column description. The specified number of stations

TABLE 5. Literature based layout data classification.

Layout ID	Flow Path Orientation			Layout Topology			Task Structure	Number of Stations
	unidir.	bidir.	mixed dir.	singleloop	multiloop	tandem	1:1,1:n,m:n	
Literature01	•				•		m:n	9
Literature02			•		•		1:n	20
Literature03		•			•		m:n	8
Literature04		•			•		m:n	8
Literature05		•			•		m:n	8
Literature06		•			•		m:n	8
Literature07		•			•		m:n	8
Literature08		•			•		m:n	16
Literature09		•			•		m:n	16
Literature10		•			•		m:n	16
Literature11		•			•		m:n	16
Literature12		•			•		m:n	16
Literature13	•				•		1:n	10
Literature14		•			•		1:n	10
Literature15		•			•	$\bullet_A$	1:n	3
Literature16		•			•	$\bullet_A$	1:n	4
Literature17		•			•	$\bullet_A$	1:n	5
Literature18		•			•	$\bullet_A$	m:n	4
Literature19	•				•		m:n	20
Literature20		•			•	$\bullet_B$	m:n	7
Literature21		•			•	$\bullet_B$	m:n	8
Literature22		•			•	$\bullet_B$	m:n	8
Literature23		•			•	$\bullet_B$	m:n	3
Literature24		•			•	$\bullet_C$	m:n	7
Literature25		•			•	$\bullet_C$	m:n	7
Literature26		•			•	$\bullet_C$	m:n	6
Literature27		•			•	$\bullet_C$	m:n	6
Literature28			•		•		m:n	9
Literature29		•			•		m:n	7
Literature30	•			•			m:n	7
Literature31	•				•		m:n	11
Literature32		•			•		m:n	11
Literature33			•		•		m:n	11
Literature34		•			•		m:n	6
Literature35	•				•		m:n	7
Literature36		•			•		m:n	11
Literature37	•				•		m:n	20
Literature38		•			•		m:n	8
Literature39		•			•		m:n	4
Literature40			•		•		1:n	7
Literature41	•				•		m:n	6
Literature42		•			•		m:n	8

represents the number of all stations in the raw data. In two compositions, the addition "used" indicates the number of stations actually served. In all other compositions, all stations are served. This information was kept to allow further layout investigations regarding the spatial arrangement. The data acquisition and treatment methods (Sections III-C, III-D, and III-E) for each composition are presented in the appendices.

In Table 5, the 42 literature based material flow and layout compositions are presented. Classified by flow path orientation, there are 8 unidirectional, 30 bidirectional, and 4 mixed directional compositions. Only one of the layouts is in the singleloop topology class, the remaining 41 are in the multiloop topology class. Of these, 12 are also part of a total of 3 tandem groups marked as $\bullet_A$, $\bullet_B$, and $\bullet_C$ in the table. All individual layouts of a tandem group are also combined in an additional, holistic layout. Among the literature layouts, two task structures are represented, 35 times $m : n$ and 7 times $1 : n$. The number of stations in the layouts from literature varies from 3 to 20 stations, with a median of 8 and a mean of 9.025. 31 material flow and layout compositions also contain further information about the coordinates, to conclude the physical location of the stations.

TABLE 6. Industry based layout data classification.

Layout ID	Flow Path Orientation			Layout Topology			Task structure	Number of stations
	unidir.	bidir.	mixed dir.	singleloop	multiloop	tandem	1:1, 1:n, m:n	
Industry01	•				•		m:n	7
Industry02	•			•			m:n	4
Industry03		•			•		m:n	15
Industry04	•			•			1:1	2
Industry05		•			•		m:n	10
Industry06			•		•		m:n	58 (33 used)
Industry07	•			•			1:1	2
Industry08	•				•		m:n	4
Industry09	•			•			1:1	2
Industry10		•			•		1:n	7
Industry11		•			•		m:n	9
Industry12		•			•		m:n	7
Industry13	•			•			1:1	2
Industry14	•			•			1:1	2
Industry15	•			•			1:1	2
Industry16	•			•			1:1	2
Industry17	•			•			1:1	2
Industry18	•			•			1:1	2
Industry19	•			•			1:1	2
Industry20	•			•			1:1	2
Industry21	•			•			1:1	2
Industry22	•			•			1:1	2
Industry23	•			•			1:1	2
Industry24	•			•			1:1	2
Industry25	•			•			1:1	2
Industry26		•			•		m:n	23 (22 used)
Industry27		•			•		m:n	6
Industry28		•			•	•D	m:n	9
Industry29		•			•	•D	m:n	10
Industry30		•			•		m:n	5

Table 6 shows the classification of 30 industry based material flow and layout compositions. 19 are unidirectional layouts, 10 bidirectional, and one is a mixed directional layout. 17 layout topologies can be classified as singleloop and 13 as multiloop topologies. The $1 : 1$ task structure exists in 16 of 30 industrial material flow and layout compositions, i.e. in more than half of them. The $1 : n$ task structure is represented once, the $m : n$ task structure 13 times, where the number of stations served varies between 4 and 33. Excluding the material flow and layout compositions with a $1 : 1$ task structure and two stations, the mean value is 9.8 stations and the median is 7 stations. In summary, it can be seen that $m : n$ task structures are considered in the majority (83%) of the material flow and layout compositions from literature whereas in the sample of 30 material flow and layout compositions from industry only 47% are considered. Similarly, only 2.4% singleloop topologies are present in the literature data with whereas in the industry data 57% of the layouts are classified as singleloop topologies.

Industry26 to Industry30 originate from the same system. Industry26 covers the entire system, whereas Industry27 to Industry30 describe subsystems in which different vehicle types are used. Industry28 and Industry29 collectively form a tandem group D in which four stations serve as transfer stations.

B. STATION OPERATION FREQUENCY ANALYSIS

Besides the structure of a layout, the distribution and operation frequency of the stations in the layout are also important with regard to operating strategies. This section focuses on the operation frequency of the stations. The operation frequency describes the relative frequency of all transport requests that start or end at a certain station. The analyses presented in this section are based on the transport matrix of all compositions. To perform the analysis, 25 data classes were established based on the previously performed classification of the data (cf. Section V-A), which can be found in Table 7 below. A class is an intersection of material flow and layout compositions that have a specific characteristic and can be assigned to literature, industry, or literature and industry based compositions.

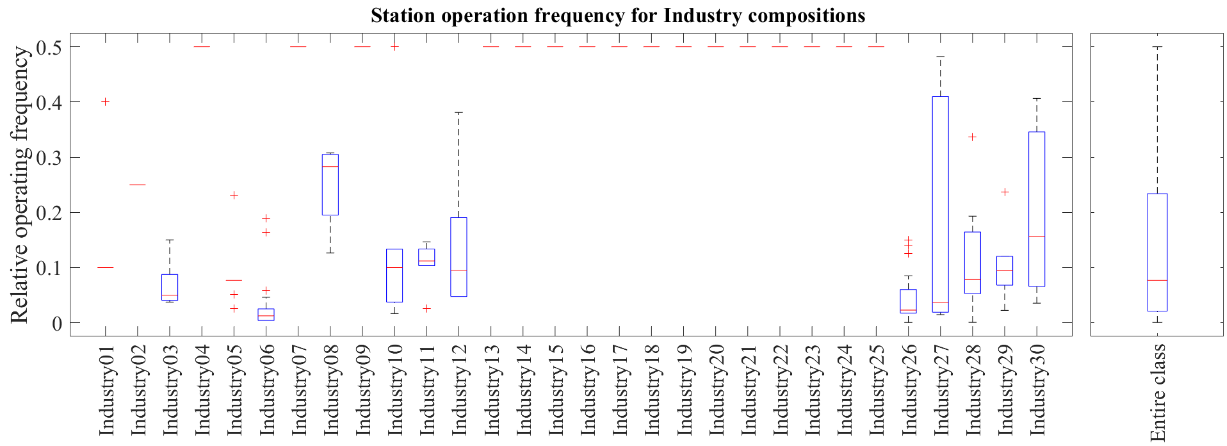


FIGURE 2. Station operation frequency analysis for industrial material flow and layout compositions.

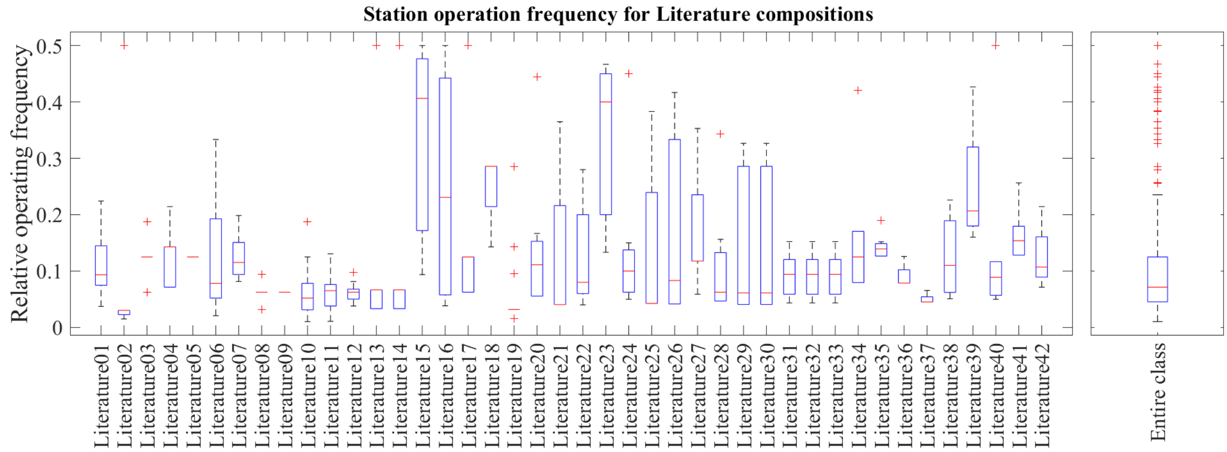


FIGURE 3. Station operation frequency analysis for literature based material flow and layout compositions.

Since there is no literature based 1:1 task structure composition in the data set, the classes of literature based task structure 1:1 and all task structure 1:1 are not considered. The station operation frequency of the material flow and layout compositions of the corresponding classes are analyzed next. The results of the analysis are presented as boxplots in Fig. 2 to 4. On the left side, the figures contain all boxplots for the compositions of station operation frequencies of the whole class, literature compositions, and Industry compositions, respectively. On the right side of each figure, there is an additional boxplot, which considers all stations of all compositions of the corresponding class and represents the distribution of the whole class.

Fig. 2 shows the station operation frequency of the industrial material flow and layout compositions. It can be seen that the distribution of the station operation frequency either shows a scattering between 0.0 and 0.5, or a constant distribution at 0.5. The exception is composition Industry02, where a constant station operation frequency of 0.25 occurs. In a singleloop layout topology, such as Industry02, each station is visited equally often. Thus, the station operation frequency is the reciprocal value of the number of stations in the singleloop (4 in this composition). As shown in Fig. 2 and 3, there is a significant amount of layouts where the station operation frequencies are low, meaning that there is no station with a

TABLE 7. Data classes and their count of compositions. N/A means not present, as data on specific characteristic is not available in the presented data set.

Characteristics	Literature	Industry	All
Task structure m:n	35	13	48
Task structure 1:n	7	1	8
Task structure 1:1	N/A	16	N/A
Flow path orient. unidir.	8	19	27
Flow path orient. bidir.	30	10	40
Flow path orient. mixed dir.	4	1	5
Layout topology singleloop	1	17	18
Layout topology multiloop	41	13	54
Layout topology tandem	12	2	14

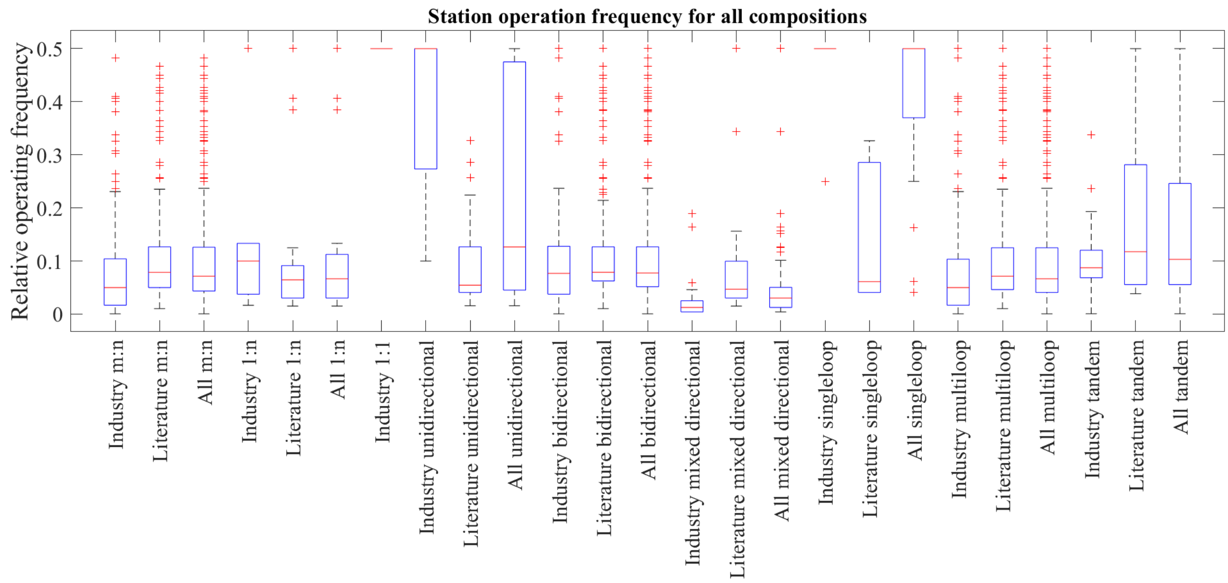


FIGURE 4. Class based station operation frequency analysis.

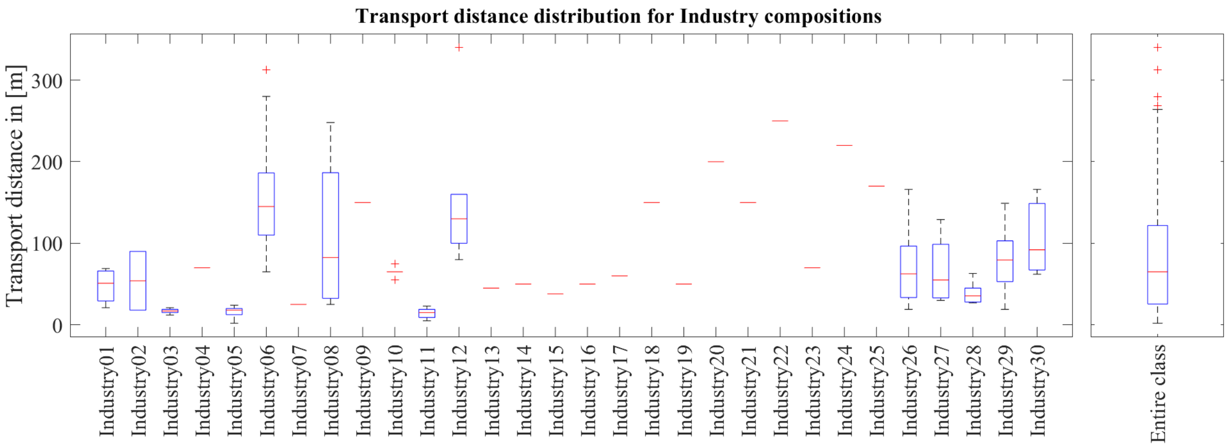


FIGURE 5. Transport distance analysis for industrial material flow and layout compositions.

dominant frequency. The following Fig. 3 shows the station operation frequency of the literature based compositions.

Comparison of Fig. 2 and 3 reveals, that more than half of the industry compositions have no scatter, while most literature data has scatter, except for Literature05 and Literature09. Finally, the analysis of the classes is presented (cf. Fig. 4), where all compositions belonging to a class are considered the set of stations.

This representation shows that only stations of the $1 : n$ and $1 : 1$ task structure classes have a maximum operational frequency of 0.5. Due to the $1 : n$ task structure, the frequency of the station on the left side is set to exactly 0.5, since all transport runs either start or end at this station. $1 : 1$ task structure compositions can only have stations with frequencies of 0.5, since these systems are defined to have exactly two stations. Since a $m : n$ task structure must have at least two stations acting as sources and at least two stations acting as sinks (cf. Section III-A3), a station operation frequency of 0.5 is not achievable. This can also be seen in the boxplots of the classes with $m : n$ task structure. The compositions of the two classes Literature $m : n$ and Industry $m : n$ shown here differ only slightly.

Fig. 4 also shows similarities of different classes. When comparing the classes of singleloop topology, $1 : 1$ task structure, and unidirectional flow path orientation, a relation can be found. Quantitatively, 17 of 19 industrial unidirectional compositions are singleloop topologies (89.5%) and 16 (84.2%) of $1 : 1$ task structure. When comparing the classes of multiloop topology, $m : n$ task structure, and bidirectional flow path orientation, another relation becomes

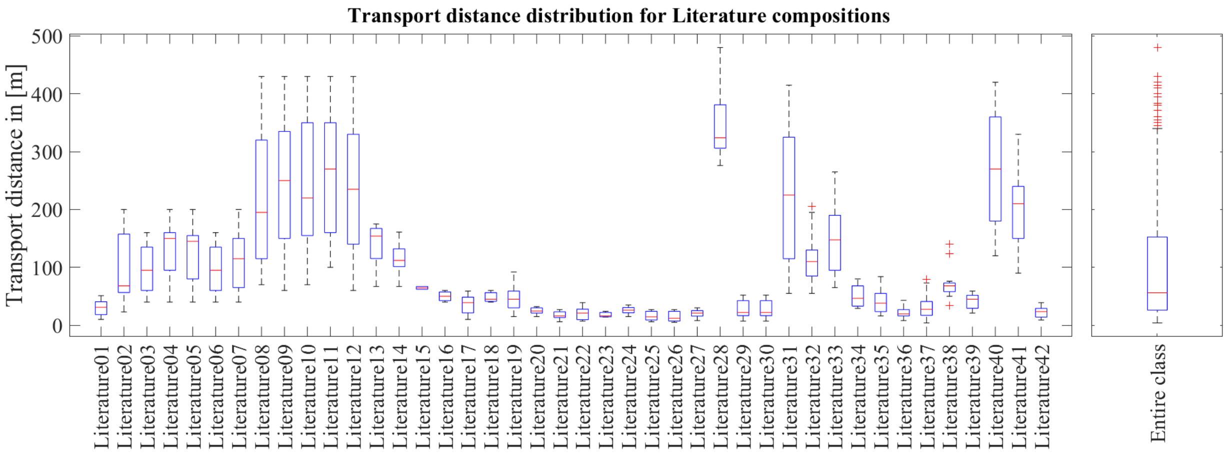


FIGURE 6. **Transport distance analysis for literature based material flow and layout compositions.**

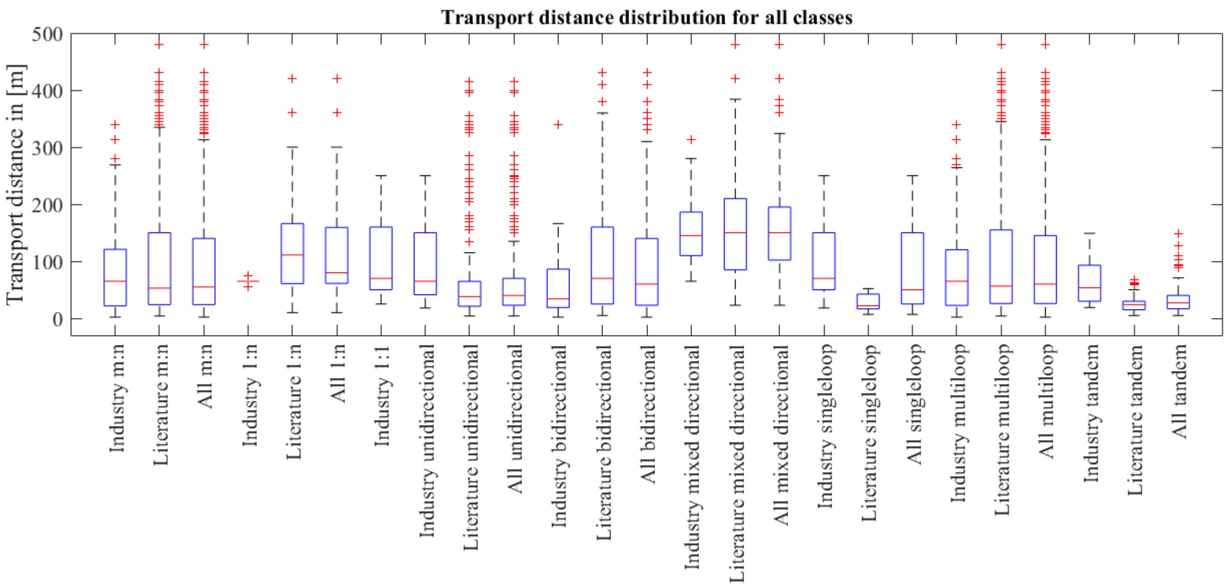


FIGURE 7. **Class based transport distance analysis.**

obvious. Out of 41 literature based multiloop compositions, 35 (85.4%) are assigned to the $m : n$ task structure. At the same time, 30 (73.2%) of the 41 compositions are assigned to the bidirectional flow path orientation. In the industry compositions, 13 are assigned to the multiloop topology, of which 12 (92.3%) are assigned of $m : n$ task structure and 11 (84.6%) of bidirectional flow path orientation. The analysis of station operation frequencies has highlighted class specific features. A significant dependence between singleloop layout topology, $1 : 1$ task structure, and unidirectional flow path orientation can be found. Another significant relation can be found between the multiloop layout topology, $m : n$ task structure, and bidirectional flow path orientation. The different layouts show very different station operation frequencies. This emphasizes the need of such data set as reference point to be able to evaluate operating strategies.

C. TRANSPORT DISTANCE ANALYSIS

Apart from station operation frequencies, transport distances between the stations and their distribution have an impact on the performance of operating strategies. Therefore, the data set was subjected to a transport distance analysis, in which the transport distances of the respective compositions were examined. The distances analyzed here are the distances of the actual transport jobs to be served from the transport matrix A_T. Similar to Section V-B, the results are presented in three diagrams, showing the transport distance distributions in boxplots. The first diagram (cf. Fig. 5) contains the transport distance distribution of the individual industrial compositions. In the same diagram, the last boxplot on the right summarizes the entire class industry, where all stations of the corresponding compositions are considered as a common set. Fig. 6 contains a similar representation for the literature based compositions.

TABLE 8. Applied data acquisition and treatment methods based on literature data.

Layout ID	A_D based on					A_T based on			Coordinates		Reference
	Distance matrix	Time matrix	Graph	Manhattan	Scaled plan	Job sequence	Job list	Transport matrix	given	assumed	based on
Literature01			•					•		•	[34], [35]
Literature02	•						•				[21]
Literature03			•		•		•			•	[3]
Literature04			•		•		•			•	[3]
Literature05			•		•		•			•	[3]
Literature06			•		•		•			•	[3]
Literature07			•		•		•			•	[3]
Literature08			•		•		•			•	[3]
Literature09			•		•		•			•	[3]
Literature10			•		•		•			•	[3]
Literature11			•		•		•			•	[3]
Literature12			•		•		•			•	[3]
Literature13			•	•		•			•		[36]
Literature14			•	•		•			•		[36]
Literature15			•	•		•			•		[36]
Literature16			•	•		•			•		[36]
Literature17			•	•		•			•		[36]
Literature18			•	•		•			•		[36]
Literature19			•	•		•			•		[36]
Literature20			•	•		•			•		[36]
Literature21			•	•		•			•		[36]
Literature22			•	•		•			•		[36]
Literature23			•	•		•			•		[36]
Literature24			•	•		•			•		[36]
Literature25			•	•		•			•		[36]
Literature26			•	•		•			•		[36]
Literature27			•	•		•			•		[36]
Literature28		•						•		•	[1]
Literature29			•					•		•	[37]
Literature30			•					•		•	[37]
Literature31			•					•			[38]
Literature32			•					•			[38]
Literature33			•					•			[38]
Literature34					•			•		•	[39]
Literature35	•							•			[40]
Literature36	•							•			[40]
Literature37	•							•			[40]
Literature38	•							•			[32]
Literature39	•							•			[32]
Literature40		•	•			•					[41]
Literature41		•						•			[6]
Literature42			•	•				•	•		[9]

Looking at Fig. 5 and 6, it can be noticed that layouts have both narrow and wide spreads in the distances. The quantitative analysis of the industrial compositions (cf. Fig. 5) shows that the minimum transport distance is 2 meters, the median is 65 meters, and the maximum value is 340 meters. For the literature based compositions, the minimum distance is 4 meters, the median is 56 meters, and the maximum distance is 480 meters. The qualitative analysis has shown that scattering of the transport distances is found for the $1:n$ and $m:n$ structures only. The last Fig. 7 contains the distributions of the transport distances in the corresponding classes as boxplots. The previous classification of the data, as well as the subsequent analysis of the data, reveal the main characteristics of the material flow and layout compositions contained in the data set. From the sample size of 72 layouts, relations among flow path orientation, layout topology, and task structure could be identified and typical quantitative metrics regarding station operation frequency and transport

TABLE 9. Applied data acquisition and treatment methods based on industry data.

Layout ID	A_D based on					A_T based on			Coordinates	
	Distance matrix	Time matrix	Graph	Manhattan	Scaled plan	Job sequence	Job list	Transport matrix	given	assumed
Industry01					•		•			
Industry02				•	•			•		
Industry03				•	•			•		
Industry04				•	•			•		
Industry05				•	•			•		
Industry06	•							•	•	
Industry07	•						•			
Industry08					•		•			
Industry09	•							•		
Industry10	•							•		
Industry11	•					•				
Industry12					•	•				
Industry13	•						•			
Industry14	•						•			
Industry15	•						•			
Industry16	•						•			
Industry17	•						•			
Industry18	•						•			
Industry19	•						•			
Industry20	•						•			
Industry21	•						•			
Industry22	•						•			
Industry23	•						•			
Industry24	•						•			
Industry25	•						•			
Industry26					•		•		•	
Industry27					•		•		•	
Industry28					•		•		•	
Industry29					•		•		•	
Industry30					•		•		•	

distance could be determined. In particular, the broad range of different transport distances in the analyzed layouts emphasizes the need of such data set as a reference to be able to evaluate operating strategies in different layouts.

VI. CONCLUSION AND FUTURE WORKS

In this paper, six different research topics were identified, which would benefit from a data set of material flow and layout compositions for benchmarking. No similar data set could be found in the literature so far. The presented data set consists of 72 material flow and layout compositions from scientific literature (42) and German industry (30). By defining and applying methods for data acquisition and treatment, all compositions were brought into a standardized, machine readable format. A taxonomy was created to allow for a better comparison of algorithms for specific layouts. Each composition was classified according to the criteria of flow path orientation, layout topology, and task structure. The final analysis of the data has shown relations among these criteria. Furthermore, the analysis shows a wide range of different transport distances. Additionally, typical key figures for transport distances and station operation frequency are presented. This data set allows for more comparable and transparent research and can be used to validate newly developed or improved planning and control methods. With the 30 layouts from the German industry in addition to the data from literature, it will even be possible to use real process data. The analysis of the layouts and their taxonomy allows to compare methods of different disciplines based on layout topologies, flow path orientations, and task structures. By providing standardized, machine readable formats, automatic tests and optimizations become possible. The data set can be used for further studies, such as energy demand modeling and energy storage dimensioning of AGVs, or the planning of charging infrastructure systems within a material flow layout. Furthermore, the development and improvement of task allocation and routing algorithms can be pursued. Finally, a comprehensive evaluation of both centralized and decentralized control strategies can be performed, providing valuable insight into their effectiveness.

APPENDIX A

See Table 8.

APPENDIX B

See Table 9.

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AUTHOR STATEMENT

Marvin Sperling: conceptualization, methodology, formal analysis, investigation, resources, data curation, writing-original draft preparation, writing-review and editing, visualization; Benedikt Schulz: writing-review and editing; Constantin Enke: writing-review and editing; Diana Giebels: resources, data curation, writing-review and editing; and Kai Furmans: writing-review and editing, supervision, management and coordination responsibility for the research activity planning and execution.

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