Chapter 2
The PRISM Taxonomy of Best Matching

Abstract This chapter presents the notion of the PRISM taxonomy of best matching along with its 3 + 1 dimensions, as a taxonomic framework for systematic identification and specification of best matching processes in various and unrelated domains. Several examples from manufacturing, supply, and service systems are presented to illustrate and exemplify the features and applications of this framework. The purpose is to enable understanding and problem solving capabilities through *analogical reasoning*—comparative analysis of different matching processes by means of the PRISM taxonomy.

2.1 Framework

The first chapter presented several examples of best matching in a wide variety of contexts and application domains. It was shown that while certain problems may seem at first to be completely unrelated to matching, they could actually be formalized as certain classes of best matching. This chapter introduces a new fundamental framework for identification and classification of different best matching processes. The goal is to provide a robust collection of modeling, design, and optimization tools for different classes of best matching problems, enabled by *analogical reasoning*—solving a problem based on the solution to its "analogous story". Before describing the mechanics of the taxonomic framework, it is worthwhile to briefly describe the notion of analogical reasoning and the way it justifies the need for such a framework in the context of best matching.

Analogical reasoning refers to a thinking process that relies on analogy, i.e., "a comparison between two things, typically for the purpose of explanation or clarification" (Oxford dictionaries). Consider *Duncker's radiation problem* (Duncker 1945) as an example:

> Suppose you are a doctor faced with a patient who has a malignant tumor in his stomach. It is impossible to operate on the patient, but unless the tumor is destroyed, the patient will die. There is a kind of ray that can be used to destroy the tumor. If the rays reach the tumor

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> all at once at a sufficiently high intensity, the tumor will be destroyed. Unfortunately, at this intensity the healthy tissue that the rays pass through on the way to the tumor will also be destroyed. At lower intensities, the rays are harmless to healthy tissue, but they will not affect the tumor, either. What type of procedure might be used to destroy the tumor with the rays and at the same time avoid destroying the healthy tissue?

A selected group of people was asked to solve the radiation problem—few people did. The reason was the *ill* definition of the problem, which essentially required an "analogy" from a remote domain to trigger creativity (Gick and Holyoak 1980). Experiments revealed that if the definition of the problem preceded a story with an analogous *convergence solution*, the majority of people would be able to solve it. The analogous story was named *attack-dispersion*:

> A small country was ruled from a strong fortress by a dictator. The fortress was situated in the middle of the country, surrounded by farms and villages. Many roads led to the fortress through the countryside. A rebel general vowed to capture the fortress. The general knew that an attack by his entire army would capture the fortress. He gathered his army at the head of one of the roads, ready to launch a full-scale direct attack. However, the general then learned that the dictator had planted mines on each of the roads. The mines were set so that small bodies of men could pass over them safely, since the dictator needed to move his troops and workers to and from the fortress. However, any large force would detonate the mines. It therefore seemed impossible to capture the fortress. However, the general devised a simple plan. He divided his armies into small groups and dispatched each group to the head of a different road. When all was ready, he gave the signal and each group marched down a different road. Each group continued down its road so that the entire army arrived together at the fortress at the same time. In this way, the general captured the fortress and overthrew the dictator.

Analogical reasoning is the foundation for creativity in humans and even in animals, the origin of new ideas. It plays a substantial role in solving problems with extensive and diverse domains, such as best matching—if an analogy is identified between two seemingly unrelated problems, the solution to one of them is indeed a great inspiration for solving the other. For example, an algorithm for parallel machine scheduling can be modified and applied for multi-enterprise network design; a protocol for micro-sensor clustering can be modified and applied for power grid design; a vehicle routing model can be modified and applied for database partitioning; a project management heuristic can be modified and applied for multi-robot team formation.

This chapter presents a taxonomic framework for all the problems in production, manufacturing, and service domains that are reducible to best matching. The framework, called the *PRISM taxonomy of best matching*, was inspired by and developed at the PRISM (Production, Robotics, and Integration Software for Manufacturing and Management) Center of Purdue University. It formalizes best matching problems with respect to 3 + 1 dimensions: D1, sets; D2, conditions; D3, criteria; D+, time or progression (Fig. 2.1). The PRISM taxonomy enables a comprehensive and standardized framework for classifying existing best matching problems and identifying new problem instances in various domains as well as effective problem-solving guidelines, all possible by analogical reasoning. The remainder of this chapter elaborates on the 3 + 1 dimensions of the PRISM

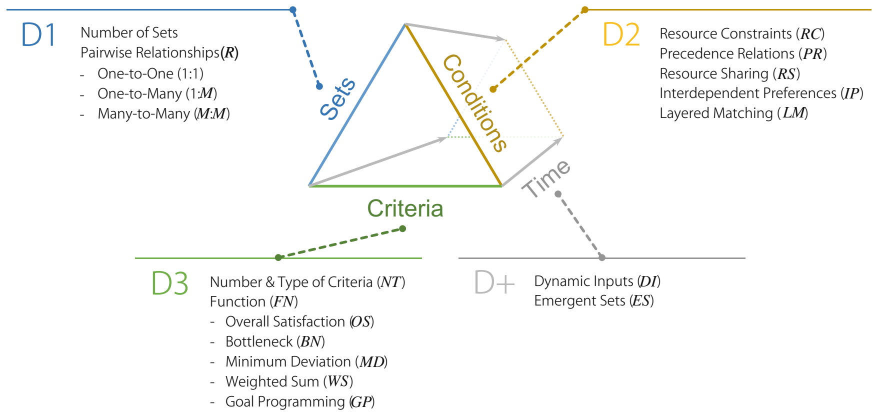

Fig. 2.1 The PRISM taxonomy of best matching (after Moghaddam and Nof 2015a)—a matching process is formally represented by its D1/D2/D3/D+

taxonomy of best matching along with several examples and illustrations. It also explains the prism structure of the four dimensional surfaces and their mutual interactions.

2.1.1 D1: Sets of Individuals

The first dimension of the PRISM taxonomy categorizes the individuals involved in being matched by the matching process into two or more *homogenous* sets; e.g., tasks and processors; students and schools; flights and passengers; items and locations; jobs, machines, and operators.[1] Note that the sets being homogenous does not imply that all the individual set members are the same, but are of the same kind or nature. The first step in formalizing a best matching process is therefore to identify the sets to be matched and their two main characteristics (Fig. 2.2): Number of sets and pairwise relations between individuals (denoted by R). Individuals can be matched to one or more elements of the other set(s)—the pairwise relations can be *one-to-one*, 1:1 (e.g., organs and patients), *many-to-one*, M:1 (e.g., tasks and agents), or *many-to-many*, M:M (e.g., suppliers and customers). In mathematical terms, each entry of R represents the pairwise relations between the elements of two sets in an ascending order of the sum of their indices, and $|R| = N(N-1)/2$. For example, in matching operators, machines, and jobs with exactly one operator assigned to each machine, $R := 1:1:M$. Accordingly, the

[1]By definition, the minimum number of sets in any matching is two sets. (See Problem 2.1) If all items in one or more sets are identical, their matching is trivial.

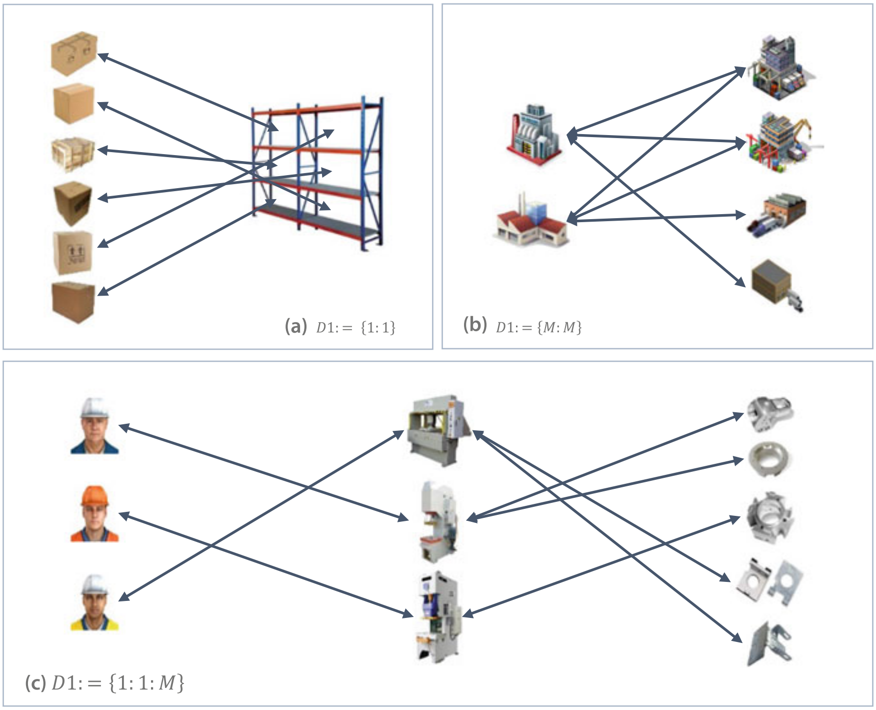

Fig. 2.2 Three matching examples. **a** Boxes and storage locations (e.g., AS/RS)—two sets on one-to-one basis. **b** Manufacturing plants and distribution centers—two sets on one-to-one basis. **c** Operators, machines, and jobs—three sets with one-to-one, one-to-many, and one-to-many relationships, respectively. [↔: matching]

first dimension of a best matching process is formally represented as $D1 := \{R\}$, which entails both the number of sets and their mutual relations.[2]

2.1.2 D2: Matching Conditions

Depending on the context and nature of the system, best matching processes are sometimes "conditional" by certain characteristics, requirements, and/or constraints, which, if disregarded, may lead to erroneous, misleading, inappropriate, or even infeasible matching results. In spite of their significant impact, however, best matching conditions (i.e., D2) have not been established well in the literature compared to the other two main dimensions of best matching (i.e., D1: sets; D3:

[2]Note that R also represents the number of sets being matched; i.e., the classification of individuals into two (e.g., tasks and processors; 1:M), three (e.g., operators, machines, and jobs; 1:1:M), or more sets.

criteria). The second dimension of the PRISM taxonomy of best matching is therefore intended to formalize various conditions[3] that may govern best matching processes. Accordingly, the D2 corresponding to a certain best matching process may involve one, some, or all of the condition types explained below.

(1) *Resource constraints* (*RC*). In matching sets *I* and *J*, the elements of set *I* may require certain amounts of resources from the elements of set *J*, which have limited resources. In Fig. 2.2c, for example, each job (i.e., set *I*) has certain processing time on each machine, while each machine (i.e., set *J*) requires limited production time in each period. The best matching results are therefore influenced by this condition, where the impacts are a function of the resource requirements of the jobs and the available resources of the machines.
(2) *Precedence relations* (*PR*): In matching sets *I* and *J*, the elements of set *I* may have certain precedence relations in their matching to the elements of set *J*. This condition may significantly influence the feasibility and optimality of best matching decisions, if the process also involves *RC*. For example, in assembly line balancing, i.e., matching tasks (set *I*) and workstations (set *J*), since each workstation can accommodate a limited number of tasks (i.e., *RC*), the set of feasible workstations for task $i_1 \in I$ is influenced by the matching of its preceding task $i_2 \in I$ (e.g., if i_2 is assigned to Workstation #2, i_1 cannot be assigned to Workstation #1 at the same time).
(3) *Resource sharing* (*RS*). In matching sets *I* and *J* with *RC* (e.g., *I*: tasks that require resources; *J*: machines with limited resources), the elements of set *J* may not be isolated, but collaborating by laterally sharing their resources with each other. Hence, the problem is to match sets *I* and *J* with respect to their resource requirements and constraints, respectively, given that the elements of set *J* (e.g., machines) are allowed to share their resources among themselves, under certain circumstances and conditions. Consider, as an example, a supply network where the supply enterprises are allowed to collaborate through *demand and capacity sharing* (see, e.g., Kutanoglu and Mahajan 2009; Yoon and Nof 2010; Paterson et al. 2011). In this specific case (Fig. 2.3), the optimal allocation of customers/demand points (i.e., set *I*) to the supply providers (i.e., set *J*)—which is done based on the correspondence between demand and capacity parameters—may be drastically influenced by the lateral collaboration decisions (Moghaddam and Nof 2014). Best matching with *RS* is indeed a special class of best matching with *RC*, where the elements of set *J* are allowed to share resources.
(4) *Interdependent preferences* (*IP*). Matching between sets *I* and *J* is essentially performed based on specific criteria, which represent the mutual *preferences* of the individuals of different sets. The matching preferences are typically fixed input parameters representing the status and characteristics of the system; e.g.,

[3]Note that although all the known and most common matching conditions—both classic and emerging—are covered in this section, D2 may also involve other types of conditions that are not discussed here.

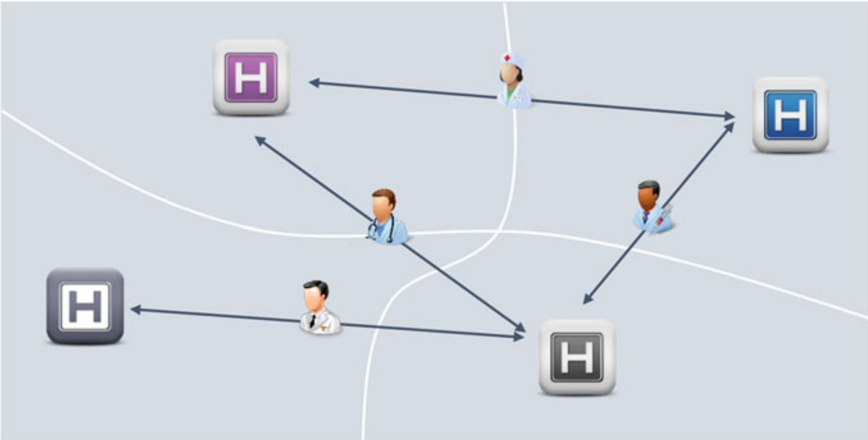

Fig. 2.3 Resource sharing in a collaborative community healthcare network. The "delineation" of the specific region that a community hospital serves, i.e., matching people (set I) and hospitals (set J) based on geographical location, is noticeably influenced by the ability of the hospitals to mutually share their resources (e.g., doctors) in case of imbalance in the regional capacity and demand. [↔: resource sharing]

cost of production; speed of delivery; quality of service; dimensional fitness. In some cases, however, the preferences are not fixed and independent of environmental and decisional factors (Moghaddam & Nof, 2015a). In two-sided matching between sets I and J, for instance, the preferences of $i_1 \in I$ for $j_1 \in J$ and $j_2 \in J$ may vary, depending on which other elements of set I have already been matched to j_1 and j_2; e.g., matching i_2 to j_1 may lead to increase, decrease, or no change in the preference of i_1 for j_1 (Fig. 2.4). For example,

- The initial preferences of students (i.e., set I) for certain course project teams (i.e., set J) may be influenced by the affiliation of strong/weak students to those teams;
- The initial preferences of jobs (i.e., set I) for different machines (i.e., set J) may be influenced by the allocation of other jobs with similar/different setups to those machines;
- The initial preferences of companies (i.e., set I) for certain suppliers (i.e., set J) may change, depending on the matching of other companies (collaborator or competitor) to those suppliers.

(5) *Layered matching* (*LM*). In certain cases, there are several necessary steps of matching. A typical case: The outcomes of a set of parallel matching processes provide the basis for a subsequent matching process. For example, in an assembly process component parts are matched according to their mutual dimensional fitness, which is considered as the matching criterion. The combination of parts (sets) I and J produces sub-assemblies Y, and the combination of parts K and L produces sub-assemblies Z; then, pairs of Y and Z are assembled in the next stage to yield the final products (Fig. 2.5).

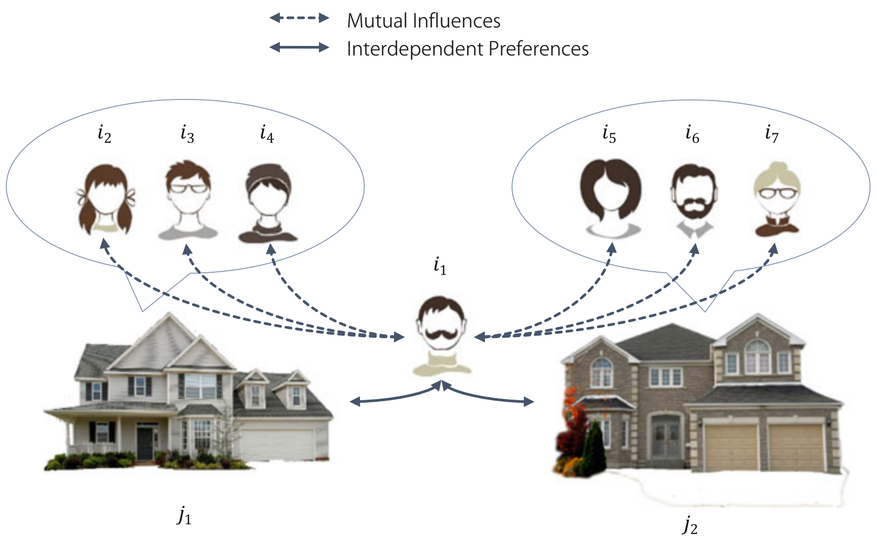

Fig. 2.4 Best matching with interdependent preferences (*IP*). Example: Mr. i_1 has to select from two houses (i.e., j_1 and j_2) and move into it. He has initial preferences for each choice (solid arrows). However, those preferences may be strengthened/weakened, depending on his impression and feelings (dotted arrows) for the current residents already settled in those houses (i.e., $i_2, \ldots, i_7$) (adapted from Moghaddam and Nof 2015a)

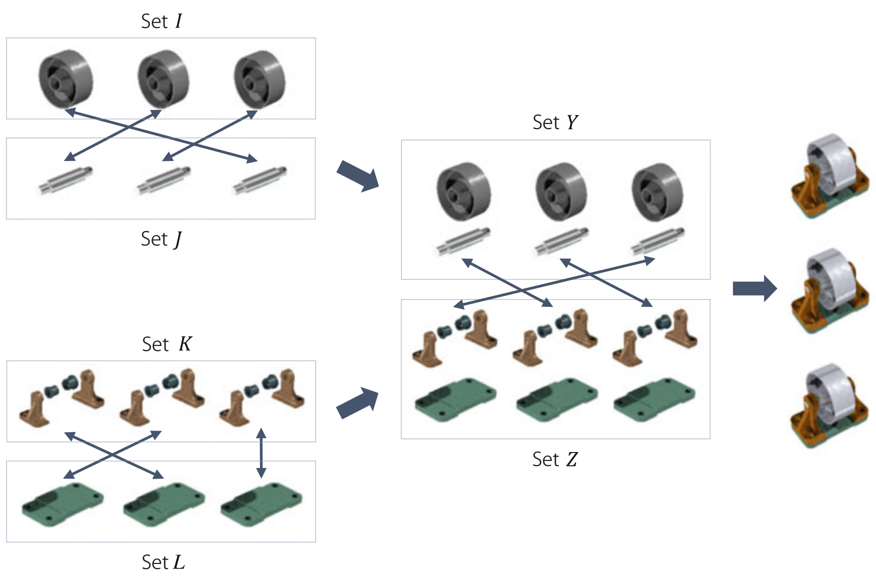

Fig. 2.5 Layered best matching in selective assembly of spin part (courtesy of IronCAD). The elements of sets *Y* and *Z*, resulted from matching sets *I* and *J* and sets *K* and *L*, respectively, in an earlier stage, are matched to produce the final products. The quality of the second stage matching (i.e., *Y* and *Z*) in terms of dimensional fitness is directly influenced by the preceding parallel matching processes (i.e., *I* and *J* & *K* and *L*). [↔: matching]

A best matching process may involve one (or more) of the aforementioned conditions. Accordingly, the second dimension of the PRISM taxonomy of best matching may include *RC*, *PR*, *RS*, *IP*, and/or *LM*. For the best matching processes shown in Figs. 2.3, 2.4 and 2.5, the second dimension of the PRISM taxonomy is represented as D2 := $\{RC, RS\}$, D2 := $\{RC, IP\}$, and D2 := $\{LM\}$, respectively.

2.1.3 D3: Matching Criteria

The *best match* is naturally distinguished from other potential matches based on a set of criteria (one or more). The goal is then to enhance the performance of the system with respect to the given criterion/criteria by optimally matching the distributed individuals. In the range of possible matches, between the mismatch and the optimal match, there are possibilities of compromise match, adequate match, and best match. Optimal match can be found only if all matched components are perfect. In practice, however, best match means the best that can be accomplished, including the case of optimal match when it is feasible. Benefits of best matching, in terms of the resulting best match, include advantages gained in the quality, effectiveness and value of design, decisions, services, products; and in the efficiency and timeliness of plans, procedures, processes, activities and responses. With respect to the matching process itself, the best matching process can be measured by its timeliness, reliability, cost-effectiveness, and so on.

The definition of "best," both for the matching process and for the resulting best match depends on the matching objectives (criteria). Various such objectives are defined and discussed throughout this book. For instance, recall the example of matching bolts and nuts (see Fig. 1.1 in Chap. 1). Suppose we want to match a set of bolts and a set of washers, such that the dimensional gap between each pair when assembled is minimal. We assume all the parts are within design tolerance, but a tighter fit would result in better quality (see Velásquez and Nof 2008, 2009). Best matching criteria are diverse and depend on the context and application domain—from traditional cost, time, efficiency, and productivity factors to emerging e-Criteria (Nof 2007) such as:

(1) *Integrability*. Ability to integrate data from a number of distributed entities and increase their relative usefulness.
(2) *Connectivity*. Type, level, and quality of ICT-supported connections between distributed operating systems, and application and network layers.
(3) *Agility*. Ability of a system, at individuals or network level, to respond and adapt to changes in real-time.
(4) *Scalability*. Ability of a process, system, or network to handle increasing amount of tasks and adapt to growth.
(5) *Reachability*. Effectiveness of interconnections and interactions between individuals in a distributed network.

(6) *Viability*. Ratio of the cost of operating/sustaining distributed individuals to the rewards gained from their respective service.
(7) *Autonomy*. Level of delegation of authority, task assignments, and decentralization in distributed networks.
(8) *Dependability*. Probability of a task to be successfully executed—including system *availability*; *reliability*; *sustainability*; *integrity*; and *maintainability*.
(9) *Resilience*. Ability to survive the unforeseen circumstances, risks, disruptions, and high impact events (*a.k.a.*, *transformability* and *adjustability*).

Although the definitions of some criteria may be completely different, their implications are the same—*desirable* criteria (e.g., agility) must be increased/strengthened while *undesirable* criteria (e.g., cost) must be decreased. Hence, without loss of generality, all matching criteria can be formalized as *preferences* of individuals for each other. Specifically, the quality of matching individuals $i \in I$ and $j \in J$ is represented by their mutual preference as

$$P_{ij} = w_i . p_{i \to j} + w_j . p_{j \to i}, \quad \forall i \in I, j \in J. \tag{2.1}$$

where $p_{i \to j}$ and $p_{j \to i}$ denote the *normalized* preferences of $i \in I$ for $j \in J$ and $j \in J$ for $i \in I$, respectively. Coefficients w_i and w_j, $w_i + w_j = 1$, denote the relative *weights* of individuals i and j in defining the mutual preferences.

The third dimension of the PRISM taxonomy of best matching formalizes the matching criteria based on the mutual preference scores. Specifically, D3 provides information on the number and type (desirable: "+"; undesirable: "−") of criteria (*NT*) along with the formulation of the respective objective function (*FN*):

- Single criterion

(1) *Overall Satisfaction* (*OS*). This classic function maximizes the overall satisfaction of preference scores, e.g., minimizing the total cost of production (D3 := $\{-, OS\}$); maximizing the overall service level (D3 := $\{+, OS\}$); minimizing the total transportation time (D3 := $\{-, OS\}$).
(2) *Bottleneck* (*BN*). This function maximizes the minimum satisfaction degree of individuals. Application examples of bottleneck assignment include (Ravindran and Ramaswami 1977):

a. Matching printing jobs and press machines in order to minimize the makespan (D3 := $\{-, BN\}$).
b. Transportation of perishable goods from warehouses to markets with minimum spoilage (D3 := $\{-, BN\}$).
c. Shipment of military supplies from warehouses to command posts in case of emergency (D3 := $\{-, BN\}$).

(3) *Minimum Deviation* (*MD*). This function minimizes the gap between the maximum and minimum satisfaction degrees (Martello et al. 1984) or the

average and minimum satisfaction degrees (Gupta and Punnen 1988). Application examples include (Duin and Volgenant 1991):

a. Cooperation between competitors on the construction of a communication network with the objective of minimizing the gap between the maximum and minimum construction and future maintenance cost $(\mathrm{D3} := \{-, MD\})$.
b. Allocation of patients with different degrees of condition severity to different test groups such that the gap between the maximum and minimum severity conditions is minimized $(\mathrm{D3} := \{-, MD\})$.
c. Assignment of tasks to machines in a project with multiple independent phases, where busy machines cannot process the tasks of other phases until the current process is finished, and the objective is to minimize the machines idle times $(\mathrm{D3} := \{-, MD\})$.

- Multiple criteria

(1) *Weighted Sum* (*WS*). This function combines the normalized values of all criteria into one—with respect to their type (i.e., desirable/undesirable)—and optimizes all criteria simultaneously via the unified function. An application example is the assignment of referees to football matches in an Italian championship (Scarelli and Narula 2002) based on multiple criteria (four in this example) such as reliability, evaluation of fitness, international prestige, and refereed matches/number of years worked $(\mathrm{D3} := \{++++, WS\})$.
(2) *Goal programming* (*GP*). This function prioritizes the criteria and considers them in sequence, based on certain target values and bounds. An application example is reallocation of remedial education teachers from the schools at which they taught in the morning to the schools at which they are to teach during the afternoon (Lee and Schniederjans 1983). The matching criteria for this matching instance were (a) the cost of travel between the schools, (b) the mutual preferences of teachers and schools, and (c) the recommendations of the teachers' supervisors, where (a) $\gg$ (b) $\gg$ (c) $(\mathrm{D3} := \{-++, GP\})$.

The objective of a best matching process can be formalized through one of the aforementioned (or similar[4]) functions. Note that based on the definition of collaboration and competition in Chap. 1, these functions are essentially useful for collaborative best matching where all individuals pursue a set of global objectives

[4]Note that although all common criteria functions are included in the third dimension of the PRISM taxonomy of best matching, the criteria functions may be formulated in other formats that are not discussed here.

that can be formulated in a single unified function. The properties and differences of competitive and collaborative best matching and their respective mechanisms are described in detail in Chaps. 4 and 6 of the book.

2.1.4 D+: Time or Progression

All three primary dimensions of a best matching process may be influenced by *time*, certain progression of time, steps, phases, frames, as an additional dimension. The dynamic and emergent behaviors of systems and their environments may evolve and change the characteristics of the sets (e.g., number of sets and elements; mutual relationships), conditions (e.g., dynamic interdependencies between preferences), and/or criteria (e.g., changes in definitions/values). Dynamic updates in the sets of subassembly parts with various dimensional tolerances (Velásquez and Nof 2008) or dynamic allocation of customers to enterprises based on their association/dissociation to/from a Collaborative Networked Organization (CNO) (Moghaddam and Nof 2015b) are among several examples of dynamic best matching processes. This additional dimension (D+) requires effective real-time optimization and control mechanisms to uphold the quality of matching over time. D+ characterizes the time-based (progression-based) behavior of best matching processes with respect to two main properties:

- *Dynamic Inputs* (*DI*). Some best matching processes may involve variations in the input parameters in real-time. For example, clusters formation in wireless sensor network is regarded as a best matching process with dynamic inputs (*DI*), because the energy levels of sensors—as one of the main criteria for matching sensors to peers/clusters—vary over time.
- *Emergent Sets* (*ES*). The number of individuals in one or more sets may vary in real-time in certain best matching processes. An example for this case is machine scheduling where the process dynamically undergoes changes in the number of jobs (due to, e.g., variations in demand; introduction of new products; saturation of old products) and/or machines (due to, e.g., breakdowns; maintenance; orders from multiple sources).

If a matching process involves neither *DI* nor *ES*, D+ is left blank in the formal representation of the PRISM taxonomy of best matching. D+ is motivated and addressed by two emerging design principles of CCT, the Collaborative Control Theory (Nof et al. 2015), which will be further elaborated in Part II of the book:

- *Association/dissociation*. In a CNO (e.g., networks of sensors; agents; robots; enterprises), this principle guides the optimality of decisions in terms of (a) the time/duration to collaborate and participate in a CNO; (b) collaborative decisions and respective outcomes; (c) the cost of participation; (d) the reasoning behind remaining in or joining a CNO; (e) the performance achieved through association/dissociation decisions. The association/dissociation principle is relevant to *DI* in the D+ dimension of the PRISM taxonomy of best matching.

- *Emergent lines of collaboration*. This principle guides (a) the quality of collaborative decision-making in complex environments; (b) cost-efficient provision of knowledge and information; (c) development of emergent networks. The principle of emergent lines of collaboration is relevant to *ES* in the D + dimension of the PRISM taxonomy of best matching.

2.1.5 The Prismatic Structure of the PRISM Taxonomy

From the definitions and explanations of the PRISM taxonomy in the previous sections it becomes clear that the three dimensions, D1, D2, and D3 interact mutually during the matching process. Furthermore, along the time or progression dimension, D+, they extend, vary and evolve to a prismatic volumetric structure (Fig. 2.1). The length of the prism represents the length of the matching process. A matching process may be short or long; e.g., completing a scheduling computation in a few milliseconds; completing a jigsaw puzzle in a few minutes; matching team members to their assignments in a few hours or days; competing in a tournament over a season; clashing and matching forces through battles over hundreds of years; exploring space to identify and match planets over many decades; and searching and matching over a lifetime to find again the unforgettable smell and flavor of your favorite childhood dish. A matching process may be completed once, repeated several times, or repeated continuously. It may also remain incomplete. These completion and repetition cases can also be illustrated by the examples in the next sections.

2.2 Four Examples of the PRISM Taxonomy Application

The logic and 3 + 1 dimensions of the PRISM taxonomy of best matching were introduced in the previous section, and several examples were presented for describing the attributes, properties and mechanisms of each dimension. In this section, four examples are selected for detailed and comprehensive illustration of the PRISM taxonomy and D1/D2/D3/D+ notation.

2.2.1 Balancing Collaborative Assembly Lines ($M : 1/RC, PR, RS/ - -, WS$)

Assembly line balancing is a process of assigning a set of tasks to a set of interconnected workstations such that their workload is balanced with respect to the required production throughput. Each task has certain duration and precedence relations with other tasks, cannot be subdivided, and must be processed at a specific workstation. The objective of an assembly line balancing problem is typically to minimize the number of workstations for a given cycle time (Type-I balancing) or minimize the cycle time for a given number of workstations (Type-II balancing). In practice, assembly lines are usually not balanceable, i.e., the overall workload is not equally distributed between all active workstations due to various technical and technological constraints. The consequences of such imbalances are underutilization of resources, bottlenecks, and low efficiency and flexibility of assembly lines. An emerging solution to shorten this gap is *collaboration* among workstations (Moghaddam and Nof 2015c, d), where partially loaded workstations share their idle *tools* (e.g., shareable equipment/workforce) with overloaded workstations during each cycle (Fig. 2.6). The result will then be less idle times and shorter cycles at partially loaded and overloaded workstations, respectively.

This matching problem can be formalized by the PRISM taxonomy of best matching as follows (and as shown above):

- D1 := $\{M : 1\}$
  - Matching a set of tasks (I) and a set of workstations (J). Tasks cannot be subdivided and must be processed at one workstation. Each workstation can process multiple tasks.
- D2 := $\{RC, PR, RS\}$
  - RC: Workstations have limited capacities (cycle time) for processing tasks.
  - PR: Tasks have precedence relations for processing.
  - RS: Workstations are allowed to share their tools with each other.
- D3 := $\{--, WS\}$
  - Two objectives with different weights are involved in the balancing decisions: (a) Minimize the cycle time; (b) Minimize the number of workstations.
- D$+$:= None.

2.2.2 Part Pairing for Concurrent Loading-Machining $(1 : 1//-, OS)$

Milling is a machining process that utilizes rotary cutters for removing materials from a work-piece. Like other machining applications, all milling processes—in spite of their diversity—begin with loading a work-piece on the machine and possibly certain setting up. During the loading process, the machine is idle, which undesirably imposes considerable costs and inefficiencies in the system. A potentially effective solution to this problem is *dual-pallet machining*—a

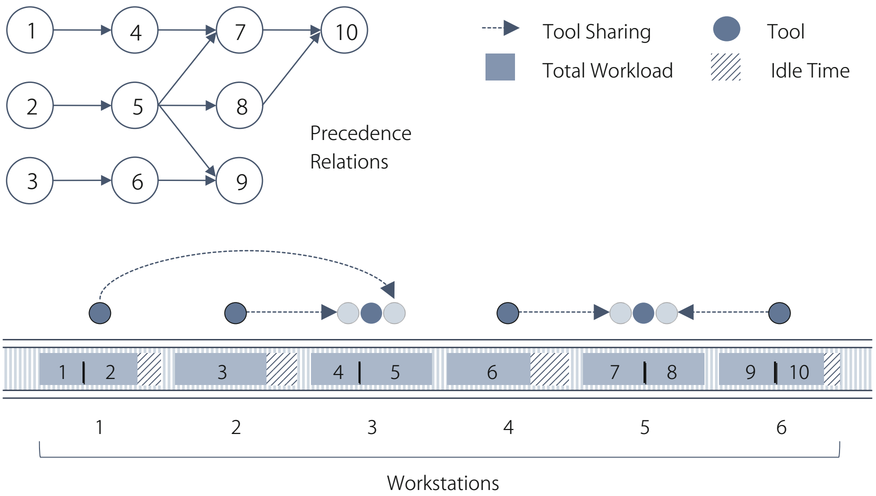

Fig. 2.6 Balancing assembly lines with collaborative workstations (after Moghaddam and Nof 2015c). The precedence relationships along with cycle time upper bounds (i.e., resource constraints) limit the set of feasible workstations for some tasks; e.g., Task 9 cannot be matched to Workstations 1–3, because its immediate predecessors have been matched to Workstations 3 and 4. The workstations are allowed to laterally collaborate through sharing their tools in order to enhance balanceability and resource utilization

configuration that enables concurrent loading and machining of work-pieces, thus minimizing idle time and inefficiencies. The work-pieces on the loading and machining pairs of dual-pallets are not necessarily identical, which makes it difficult to fully materialize the potentials of this configuration. That is, if the loading and processing times of the parts on each one of a dual-pallet pair are significantly different, the process still suffers considerable idle times. For example, if the parts on Pallet #1 require processing time of 4 min, and the parts on Pallet #2 require loading time of 10 min, the machine will be idle for 6 min after processing a part from Pallet #1 (Nof et al. 1979).

Consider a milling process with dual-pallet machining configuration (Fig. 2.7a), where different types of work-pieces are assigned to similar pallets (the same size) and have specific loading and machining times. Due to limitations in the number of fixtures, Pallets #1 and #2 cannot contain similar work-pieces. The total idle time of the milling machine can therefore be minimized by finding the best one-to-one match between set I (i.e., set of work-pieces) and itself, based on loading-machining time gaps, subject to not matching the same element of I (i.e., work-piece) to itself (Fig. 2.7b). This matching problem can be formalized by the PRISM taxonomy of best matching as follows:

- D1 := {1 : 1}
  - Matching the set of work-pieces (I) to itself. Each work-piece must be matched to one other work-piece for concurrent loading and machining.

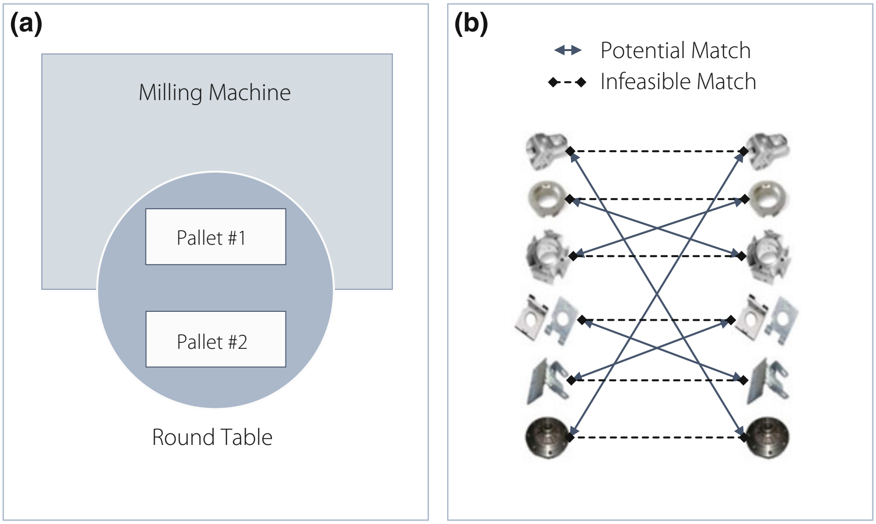

Fig. 2.7 **a** Double-part milling machine configuration (courtesy of Kirby Risk Precision Machining)—Pallets #1 and #2 are under the machining and loading processes, respectively. **b** Examples of potential and infeasible matching. A work-piece cannot be matched to itself. The matching is "symmetric"; i.e., in matching I_L (*left-side* set) and I_R (*right-side* set), matching $A \in I_L$ and $B \in I_R$ implies matching $B \in I_L$ and $A \in I_R$ as well

- D2 := None[5]
- D3 := $\{-, OS\}$
  - The objective is to minimize the gap between loading time of the work-pieces in Pallet #1 and processing time of the work-pieces in Pallet #2, and vice versa. In order not to match a work-piece to itself, the corresponding gap parameters must be replaced by sufficiently large numbers in the objective function.
- D+ := None.

2.2.3 *Dynamic Teaming with Interdependent Preferences* $(M : 1/RC, IP/+, OS/DI, ES)$

A team is a collaborative network of individuals (e.g., genomes; social insects; humans; sensors; machines; projects; factories) that interact through sharing information, resources, and responsibilities to accomplish a set of common goals

[5]The matching process does not involve any specific conditions, except for not matching a work-piece to itself, which can be handled by slight modifications in the objective function.

(i.e., team members are incented to collaborate). According to Tuckman's forming-storming-norming-performing model of group development (Tuckman 1965), the very first step in conducting any collaborative activity is to group homogenous/heterogeneous individuals into a set of teams. In this context, teaming refers to a best matching process performed on a set of individuals (I) and a set of teams (J), considering certain conditions and criteria.

In a network of teams, *interdependencies* among the preferences of individuals can have significant impacts on quality and performance. *Social communication* is essential for creating and sustaining relationships in teams. Any social interaction and its aggregated effectiveness are indeed influenced by *interpersonal relationships*, *relational messages*, and *emotion*. Emotions may influence the preference of individuals for a team and subsequently their performance, depending on *who their teammates are*. Such mutual influences are classified as *altruism*, *envy*, and *neutrality*—if Person A is altruistic/envious/neutral about Person B, and Person B is already a member of Team Z, the preference of Person A for Team Z is increased/decreases/not changed (Moghaddam and Nof 2015a). To better understand this concept, recall the example of Mr. i_1 who was looking for a new house (Fig. 2.4), where his initial preferences for each house (≡ team) were influenced by the people (≡ team members) already living at each house.

Teams are typically formed in a way that the overall performance, harmony, and/or satisfaction of individuals are optimized. This process, however, may evolve over time; i.e., involve changes in the individuals' preferences, performance, and mutual influences, and/or the number of individuals/teams. Examples for the latter case, association/dissociation behavior, include arrival/departure of a job to/from a production cell; allocation of new interns/students to hospitals/schools; temporary or permanent loss of a team member or leader; opening/closing a line in a service system such as a bank; establishing a new school/hospital (Fig. 2.8). Given all these cases, the team formation problem with interdependent preferences can be formalized by the PRISM taxonomy of best matching as follows:

- D1 := $\{M : 1\}$
  - Matching a set of individuals (I) and a set of teams (J). Each individual must be a member of exactly one team, while each team may be composed of multiple individuals.
- D2 := $\{RC, IP\}$
  - RC: Each team can accommodate up to a certain number of individuals.
  - IP: There are interdependencies among the preferences of individuals for teams.
- D3 := $\{+, OS\}$
  - The objective is to maximize the overall performance of the teams, or the overall satisfaction of the individuals.
- D+ := $\{DI, ES\}$

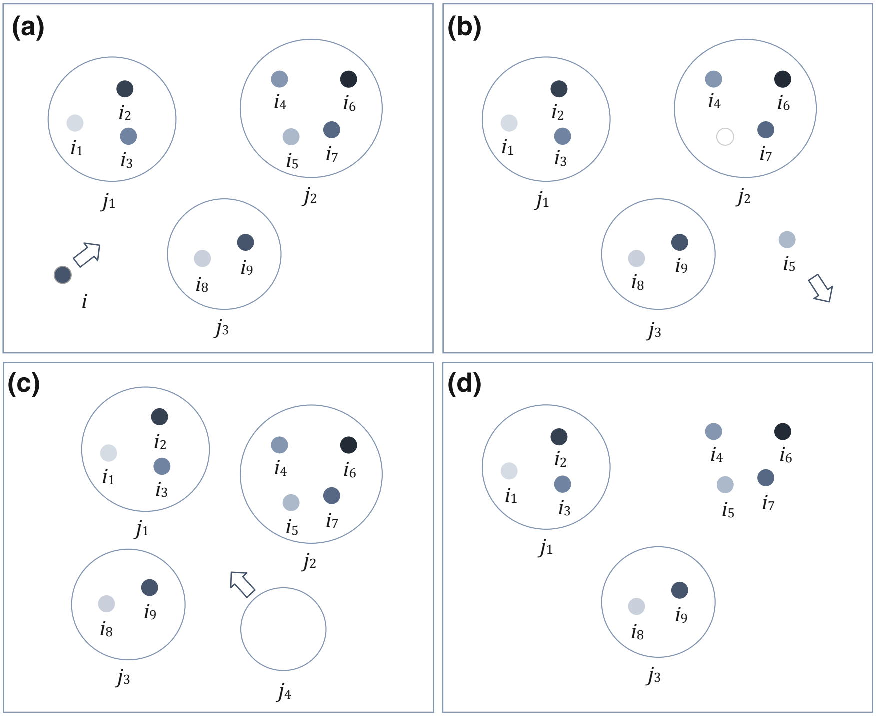

Fig. 2.8 Evolution of a network of teams; e.g., dynamic alliances of enterprises. **a** Association or a new enterprise to the network of alliances $(i_{10} \in I)$. **b** Dissociation of an existing enterprise from the network of alliances $(i_5 \in I)$. **c** Formation of an alliance $(j_4 \in J)$. **d** Dissolution of an alliance $(j_2 \in J)$ (after Moghaddam and Nof 2015a). [⇨ : Association/Dissociation]

- *DI*: The individuals' preferences for teams and their mutual influences on each other, the teams' preferences for individuals and their capacity limits, and other system's characteristics may vary over time.
- *ES*: New individuals/teams may *associate* with the system and old individuals/teams may dissociate from it (Fig. 2.8).

2.2.4 *Location-Allocation Decisions in CNO* $(1 : M : M/RC, PR, RS/+-, WS)$

CNO (Collaborative Networked Organizations) are organizations—systems of resources deployed for processing and synthesizing a set of tasks—of autonomous, distributed, and comprising heterogeneous individuals that collaborate through sharing information, resources, and responsibilities to achieve common and compatible goals (Camarinha-Matos et al. 2009). The definition of CNO stands for a wide variety of systems. For example, (see Moghaddam and Nof 2015e)

- A procurement system with a network of order, product, and resource agents.
- A community healthcare network with a set of hospitals, equipment, personnel, and doctors.
- An intelligent warehouse system with a network of sensors/RFID tags, readers, and antennas.
- A virtual factory with a set of decoupled software tools, shop floor devices, communication and computational elements, middleware, knowledge bases, and servers.
- A manufacturing network with a set of suppliers, distributers, and manufacturing plants.

To address the emerging needs of CNO for higher scalability, resilience, and flexibility (Putnik et al. 2013), interaction and collaboration among distributed *organizations*, *resources*, and *tasks* must be carefully designed and optimized. With the rising dominance of e-Work and e-Activities in manufacturing, business, and service (Nof et al. 2015), organizations are rapidly transforming into cyber-physical networks of resources, shared through cloud-based information and communication channels (Xu 2012) for concurrent processing of remote tasks (e.g., cyber control of tele-robots; virtual manufacturing; remote modeling/simulation/problem-solving). These emerging features demand a new definition of the classic *location-allocation problem* (Fig. 2.9):

In a CNO with a set of organizations, resources, and tasks, what are the best organization to 'locate' each resource and the best set of resources to 'allocate' each task, given that organizations can collaborate by sharing their resources and tasks?

The above problem is known as *Collaborative Location-Allocation Problem* (CLAP) (Moghaddam and Nof 2015b). The CLAP is indeed a problem of 3-way

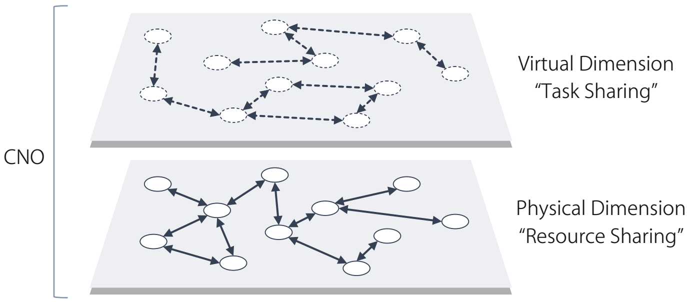

Fig. 2.9 Best matching enhances the performance of CNO at both physical and virtual/cyber levels by optimal location of resources and allocation of tasks over time (after Moghaddam and Nof 2015b). [O: organization]

matching of organizations, resources, and tasks. The PRISM taxonomy of best matching formalizes the CLAP as follows:

- D1 := $\{1 : M : M\}$
  - Matching a set of organizations (*I*), a set of resources (*J*), and a set of tasks (*K*). Multiple resources can be assigned to one organization, while each individual resource can be located in one organization. Each task must be assigned to exactly one organization, while an organization can process multiple tasks. Each resource can be used for processing multiple tasks and each task can be processed by multiple resources.
- D2 := $\{RC, PR, RS\}$
  - *RC*: Each organization can accommodate a limited amount of resources and each resource can process a limited amount of tasks.
  - *PR*: Tasks may have precedence relations for processing.
  - *RS*: Organizations are allowed to share their shareable resources and tasks with each other, given potential capacity shortage/surplus over time due to dynamic variations in demand and capacity.
- D3 := $\{+-, WS\}$
  - Different objectives can be considered in the CLAP; e.g., maximizing task fulfillment rate and minimizing collaboration cost, each with specific weights.
- D$+$:= None.

2.3 Summary

The PRISM taxonomy of best matching presented in this chapter provides an effective foundation for synthesis and formal representation of best matching processes with respect to 3 + 1 dimensions. The motivation lies in its three functions (Fig. 2.10):

(1) *Identification*. With concrete decomposition of a best matching process with respect to the characteristics of the sets of individuals, potential matching conditions, criteria, and real-time behavior, the PRISM taxonomy provides a powerful tool for scrutinizing various processes and systems in different manufacturing and service domains, and characterizes them as different classes of best matching processes.

(2) *Specification*. The PRISM taxonomy enables hierarchical representation of best matching processes in various domains by defining and quantifying four dimensions and their sub-categories—it generates standardizes best matching processes, empowers problem-solving capabilities, and helps with identification of new processes.

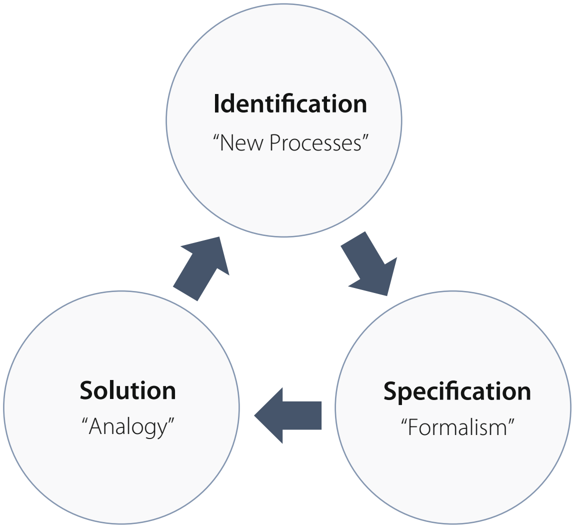

Fig. 2.10 Three functions of the PRISM taxonomy of best matching

(3) *Solution*. The PRISM taxonomy triggers analogical reasoning—as the origin of new ideas and human creativity—by enabling analogical comparisons between best matching processes from completely unrelated domains. This, in turn, leads to inspirations from the already existing solutions to analogous problems for solving unsolved problems.

The taxonomy introduced in this chapter is the basis for the rest of discussions throughout this book. Chap. 3 presents detailed mathematical formulations of various classes of best matching processes, based on the given classification by the PRISM taxonomy. Chaps. 4–6 provide solutions to different classes, and elaborates further on the impact of analogical reasoning on problem solving in this domain.

Problems

2.1. Discuss several reasons why the authors chose the prism shape for The PRISM taxonomy of best matching. Include also the optical perspective: It is represented as a "prismatic taxonomy" (Fig. 2.1) by a triangular geometric shape of a prism with rectangular sides; such optical prisms are used for light reflection/refraction.
2.2. Compare and contrast problems that can be solved by a single matching solution process, and those that require repeated matching solutions.
2.3. Explain the factors that influence the duration of a single matching process. Can this duration be shortened? Explain how.
2.4. Consider the robustness of the match, and explain how you can increase this robustness.

2.5. Consider the matching taxonomy Sect. 2.2.1. How would the taxonomic representation change in each of the following cases (each case is independent of the others)?

(a) There is no tool sharing.
(b) Tool sharing is allowed only between pairs of contiguous workstations; i.e., 1 and 2; 2 and 3; 3 and 4, etc.
(c) The line can be designed with only two workstations.
(d) There are no precedence relations among tasks.
(e) The workstations are self-improving by machine learning.

2.6. Explain the meaning of the following taxonomic representations in the context of Sect. 2.2.1:

(a) $1:1/RC, RS/-, BN/DI$
(b) $M:1/RC, PR/+-, GP$

2.7. How would the taxonomic representation in Sect. 2.2.2 change in each of the following cases (each case is independent of the others)?

(a) The round table has six pallets for pre-loading of parts (work-pieces).
(b) In addition to matching of work-pieces, they have to be matched to available times based on the maintenance schedule of the milling machine.
(c) The work-pieces have precedence relations with other work-pieces.
(d) Each work-piece has to also be matched with its accompanying tool-kit.
(e) Historical quality inspection results from machining of each work-piece type guide adaptive machining process planning for future work-pieces.

2.8. Explain the meaning of the following taxonomic representations in the context of Example 2.2.2:

(a) $M:1//+, BN$
(b) $1:1//-, OS/ES$

2.9. Consider a warehouse system where various items continuously arrive and have to be assigned to different storage locations. The storage allocation heuristic must follow two main criteria: (1) Frequency of arrival/departure (*a.k.a.*, ABC classification); (2) Mutual "affinity" of items (i.e., the possibility of being ordered together).

(a) Identify the matching processes associated with this system.
(b) Formalize the matching problem(s) identified in (a) using the PRISM taxonomy of best matching.
(c) How many sets of individuals are involved? What are the matching conditions and criteria? Is there any dynamicity (time/progression) involved in the process? Explain your answers.

(d) Which of the four examples of the PRISM taxonomy application (Sect. 2.2) better characterizes this problem? Justify your answer.
(e) Is there any relationship between the notions of product affinity and interdependent preferences? Explain your answer.

2.10. Answer Problem 2.9 assuming that the items must be carried to their locations using a limited number of AGVs (Automated Guided Vehicles).

2.11. Consider the three matching examples shown in Fig. 2.2. Explain how potential interdependencies among preference may influence the outcomes of those matching processes.

2.12. Consider the following cases associated with the example of selective assembly of spin parts shown in Fig. 2.5:

- *Case 1*: Sets *I* and *J* are matched to generate Set *Y*. Sets *K* and *L* are matched to generate Set *Z*. Sets *Y* and *Z* are matched to generate the final products.
- *Case 2*: The elements of Sets *I*, *J*, *K*, and *L* are matched simultaneously to generate the final products.
- *Case 3*: Sets *I* and *L* are matched to generate Set *U*. Sets *K* and *J* are matched to generate Set *W*. Sets *U* and *W* are matched to generate the final products.

Identify the conditions in which the outcomes of the following cases are the same or different: (a) Cases 1 and 2; (b) Cases 1 and 3; (c) Cases 2 and 3; (d) Cases 1, 2, and 3. Explain the potential cause(s) of these similarities/differences.

2.13. Develop several taxonomic representations for the following matching problems. For each, explain your assumptions and specify the meaning of the taxonomic representations.

(a) A simple assembly line balancing problem.
(b) Construction project scheduling.
(c) Assigning emergency response vehicles and crews to locations.
(d) Seating guests at a formal dinner.
(e) Selecting the best name for a new product from a list of proposed names.

2.14. Apply the PRISM taxonomy of best matching to the following problems:

(a) Matching in each of the five fundamental assembly models: chain assembly; base assembly; arithmetic assembly; geometric assembly; and combinatorial assembly (Nof et al. 2013).
(b) Sorting fruits according to quality and size.
(c) Quality inspection in a furniture production facility.
(d) Selective assembly of jet engines.
(e) Testing knowledge of recruits.
(f) Matching experiments during drug research.
(g) Investment portfolio building.

(h) Error classification.
(i) Selecting recipes for a restaurant menu.
(j) Selecting a surgeon for one's surgery.

2.15. Five matching conditions were presented in this chapter, representing the D2 dimension of the PRISM taxonomy of best matching. Identify and explain 1-3 other matching conditions that are presented here by providing practical examples and illustrations.

2.16. Explain if/how the PRISM taxonomy of best matching enhances understanding of matching processes and development of matching solutions through "analogical reasoning".

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