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HVAC CAD LAYOUT TOOLS: A CASE STUDY OF UNIVERSITY/INDUSTRY COLLABORATION[1]

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ABSTRACT

An effective partnership between industry and the university resulted in the system of design tools for the layout of HVAC systems presented in this paper and illustrated with the design of a heat pump. The system provides tools to assist in the placement of components and routing of tubes between the components. Traditional tubes, tubes that have minimized length and number of bends, and those that are impossible to route in the traditional manner, are generated. The paper provides insight on both the collaborative research interaction and the resulting set of tools.

1. INTRODUCTION

The need for greater competitiveness in a global marketplace has increased pressures on companies to reduce design cycles and time-to-market. Among these companies, Carrier has recognized the importance of developing CAD technology to assist in this design process. The design of HVAC systems, Carrier's product, is a long and tedious process, often requiring weeks to design and refine a single design concept followed by additional time to physically prototype it. Residential HVAC units in particular are typically synthesized as a mix of purchased and custom-designed components; the size and shape of the container and other stylistic aspects are given to the layout designer, as is this component set. The system design task is to arrange these components within the container to meet a market demand for performance, quality, and price, at a profit sufficient to justify the producer's investment. Much of the cost that the producer ultimately incurs can be traced back to component selection and layout. Costs determined at layout are described as constraints imposed by assembly, service, and manufacturing.

One particularly important constraint on component positioning is supplied by the need to connect the components with essentially rigid copper tubes whose shapes are constrained by tube bending equipment. This task is both difficult and critical because a slight change in the position of a component, or a substitution of one component for another functionally identical one, can require a complete redesign of the tube routes. When the routes are extremely costly or infeasible the components must be further repositioned and, again, the tubes often completely redesigned. Unfortunately there is currently no way to tell how costly the tube will be when the components are placed until the route is designed. Thus, tube routing and component positioning are tightly interconnected problems requiring repeated iteration. To further complicate the design cycle, at critical points it is necessary to physically prototype and test the concept. Through this elaborate process, the design of even a single tube route between two components can take up to two weeks in the worst case.

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Tools to assist in layout and routing for HVAC systems could decrease design time significantly. This paper presents a case study of a collaborative research approach used to create such technologies. Tools resulting from this collaboration generate:

- initial component placement within HVAC equipment;
- traditional tube routes;
- innovative, cost-effective, and complex tube routes;
- concurrent component placement and tube routing.

The tools provide the designer with various means to assist in the layout and routing process based on the current problem. The tools do not automate the entire process, but rather serve as an aid by providing partial automation. Thus, the designer remains an integral part of the process -- It is difficult to completely articulate the desired characteristics and evaluation criteria for a design and thus to completely automate the design process. Rather, the tools rapidly generate multiple alternatives, based on major evaluable objectives, from which the designer can begin further modification. Further, the tools ensure compatibility with the intended manufacturing process, provide input to analysis codes, and allow rapid redesign in case of component substitution.

A detailed discussion of related work on packing (Cagan, 1994; Coffman *et al.*, 1984; Dowsland and Dowsland, 1992; Dyckhoff, 1990; House and Dagli, 1992; Kämpke, 1988; Kawakami *et al.*, 1991; Szykman and Cagan, 1993), layout (Flemming *et al.*, 1992; Fujita *et al.*, 1991; Kim and Gossard, 1991; Landon and Balling, 1994; Sandgren and Dworak, 1988; Udy *et al.*, 1988), and routing (Asano *et al.*, 1987; Conru and Cutkosky, 1993; Gunn and Al-Asadi, 1987; Jain *et al.*, 1992; Jajodia *et al.*, 1992; Mitsuta *et al*., 1986; Park *et al.*, 1994; Wu *et al.*, 1992; Zhu and Latombe, 1991) of systems can be found in (Szykman and Cagan, 1994, 1995 a and b). Of specific relevance, Fujita and Akagi (1995) describe a layout approach applied to air conditioning design that uses knowledge-driven networks to produce rough positioning of components followed by refinement.

The research summarized in this paper resulted from an effective research partnership between industry and the university that developed over a two year period. In the next section we will discuss the interactions and responsibilities of the parties. Then the resulting series of tools will be summarized and illustrated through the design of a heat pump.

2. PARTNERSHIP APPROACH

The goal of university-industry collaboration is to move advanced methods from research, through development, and into the production processes of the firm. Typically, there are several organizations involved. First, there are those devoted to the task of designing and producing the product itself. This group has a unique understanding of the design process and product, but generally has little time or incentive to address long-term structural changes to the tools and methods used. Second, many companies have an advanced technology group whose role is to identify methods and tools that can be beneficial in the mid- to short-term time horizon. This group has a good perspective on the nature of the business and the product but is not charged with producing product. Third, large corporations often maintain a separate, central R&D facility. Researchers at this facility are able to identify and advance leading-edge approaches to solving the more general problems that underlie the firm's production processes. Finally, academic researchers have the ability to advance the leading edge of knowledge. Often they address idealized problems in which significant intellectual progress can be made by focusing on the essential aspects of a general problem. We believe that in the long run, production processes are improved most effectively by R&D methodologies that recognize the unique capabilities and perspectives of each group and play to the strengths of each organization.

In this effort, the advanced technology personnel at Carrier interacted with systems designers to understand the technological issues that limit their productivity. The designers identified tubing design and component layout as their most frequent tasks. In terms of tube routing, the need for constant modification in the face of component substitution and the need to generate tube routes that complied with the standards of particular manufacturing sites were of primary difficulty. In terms of component placement, the ability to accommodate alternative system components was seen as critical.

Based on this investigation, the advanced technology group at Carrier decided to pursue technologies to address these needs. They formulated a team from among their personnel, a researcher from the central corporate technology center (United Technologies Research Center -- UTRC), and a group of researchers at Carnegie Mellon University (CMU). The advanced technology group focused on a system-level problem definition and delivery of the system to the designers; as well they took responsibility for coordinating and managing the overall effort. The UTRC researcher and one of the advanced technology personnel formed an R&D team to address short- to mid-term development issues. This R&D team had an immediate concern for the modeling of HVAC products and the generation of traditional tube routes between components within a CAD environment. Using the object-oriented geometric modeling system ICAD, they developed a knowledge-based strategy toward the generation of tube routes based on designer classification of acceptable routes.

CMU was given the responsibility for creating advanced technologies which the R&D team would incorporate within their in-house design tools, making any modifications as needed for the Carrier-specific problem and system. Thus the CMU researchers did not need to be concerned with the low-level details of the Carrier design system, allowing them to develop problem-independent approaches to layout and routing. This approach allowed CMU to pursue the long-term research agenda, while the R&D team pursued shorter-term technology development, and the advanced technology team focused on delivery of the resulting technology.

Although these directions were the primary roles for each team, a synergy developed where the industry team provided intellectual direction and interaction for the university team and the university team provided an outside, critical view of the system approach laid out by industry. Through mutual respect and support, the teams together identified new research directions. Both groups were open to suggestions from the other: The university approach and perspective was initially different than that needed for the particular project; through a flexible approach to pursuing the research, the direction and methodology changed. Industry, too, was open to new ideas, modifying the immediate and long-term objectives based on the suggestions, research results, and discussions and arguments that ensued.

The resulting relationship led to a successful research and development collaboration. The remainder of this paper will summarize the technology created and its application to the design of a heat pump.

3. COMPONENT LAYOUT AND ROUTING SYNTHESIS

In this section we briefly present the technical approaches toward the synthesis of layouts for HVAC applications. While performance of HVAC systems is measured according to a variety of criteria, HVAC product layout tasks can be characterized on first order by four general objectives: achieving high packing density (due to trends in product miniaturization), fitting components into a specified container, minimizing tube costs, and satisfying spatial constraints on component placement including the effects from tube routes. To address these needs, four layout tools were created:

- The first uses a simulated annealing-based algorithm to lay out components within a container subject to spatial constraints.
- The second tool takes a set of placed components and uses a classification of traditional plane-orthogonal routes (discussed in Section 3.2) to automatically generate a feasible tube route.
- The third tool uses simulated annealing to generate shorter, non-orthogonal routes with fewer bends that are more cost-effective.
- The fourth tool takes advantage of the tight coupling between placement and routing; feedback and iteration occurs automatically and components are placed to minimize routing costs.

The first three tools are described below, and the fourth tool is described in Szykman (1995).

3.1. Component Placement

A simulated annealing-based approach to three dimensional component layout is used to generate optimal component placements. In the sections that follow, we describe the simulated annealing algorithm, the spatial constraint language incorporated within the layout algorithm, and the formulation of the optimization problem for component layout. More detailed descriptions of each of these elements as applied to general layout problems can be found in (Szykman and Cagan, 1994, 1995a) and (Szykman, 1995).

3.1.1. Simulated Annealing To summarize the simulated annealing algorithm (Kirkpatrick, *et al.*, 1983): an initial (design) state is chosen and the value of the objective function for that state is evaluated. A step is taken to a new state by applying a move, or operator, from an available move set. This new state is evaluated; if the step leads to an improvement in the objective function, the new design is accepted and becomes the current design state.

If the step leads to an inferior state, the step may still be accepted with some probability. This probability is a function of a decreasing parameter called *temperature*, based on an analogy with the annealing of metals. The temperature starts out high and decreases with time. Initially, steps taken through the state space (and therefore the objective function space) are almost random, resulting in a broad exploration of the objective function space. As the probability of accepting inferior steps decreases, those steps tend to get rejected, allowing the algorithm to converge to an optimum once promising areas of the objective function space have been found.

For each iteration in the simulated annealing algorithm, the design is perturbed using a move from the move set, and the new design is evaluated according to the objective function. The move set for the component layout algorithm consists of three types of moves: *translate*, which changes the location of a component, *rotate*, which changes the orientation of a component and *swap*, which exchanges the locations of two components. The moves are selected randomly (though not necessarily with equal probability) and applied to a random component.

3.1.2 Spatial Constraint Language A language of spatial constraints has been implemented in conjunction with the simulated annealing algorithm to allow designers to impose a variety of constraints on component placement that are characteristic of HVAC product layout problems. The language allows constraints to be applied to component locations or orientations, or to specify desired component proximities. Constraints can be imposed based on a global coordinate system or relative to locations and orientations of other components, and can take the form of conjunctions or disjunctions of constraints (*i.e.*, sets of constraints all of which must be satisfied, or sets of constraints any one of which must be satisfied).

If a component has all of its constraints satisfied, it is said to be in a feasible region of the design space. In this approach to layout generation, equality constraints are satisfied and propagated throughout the annealing run. Inequality constraints, however, are permitted violations and penalized in the objective function. As the algorithm runs, penalties in the objective function are driven to zero by moving components which are in an infeasible region toward a feasible region.

3.1.3 Formulation of Optimization Problem To allow designers to optimize a variety of design objectives, the problem formulation utilizes a generic objective function, F, consisting of a weighted sum of the form:

$$F = W_1 C_1 f_1 + W_2 C_2 f_2 + ... + W_n C_n f_n, \qquad (1)$$

where f_i are the design objectives or violation penalties, C_i are coefficients used to avoid scaling problems by normalizing objectives or penalties that may differ in order or magnitude, and W_i are weights that indicate relative importance of each of the normalized terms. The objective function for component placement includes five terms: one design objective and four penalty terms. The design objective is the inverse of a measure of packing density, which when minimized, results in maximizing packing density.

The simulated annealing algorithm performs best when it is permitted to move through infeasible regions of the design space. Thus, the algorithm can generate designs where components intersect one another or protrude from a specified container. Since such designs are not desirable as final designs, these violations are eliminated by penalizing them in the objective function. The first two violation penalty terms penalize component intersection and container protrusions. The second two violation terms penalize violations of inequality constraints and of proximity constraints, respectively. No penalty term is required to satisfy equality constraints because they are satisfied through constraint propagation, as described above.

The minimization of the objective function directs search toward valid, or feasible, designs by driving the penalty violations to zero. Once all violation terms are equal to zero, the sole remaining objective in the optimization is the inverse-density term. This term was used in this work because it is a problem-independent objective that is applicable to a variety of problems. Additional problem-specific design objectives can be incorporated into the generic objective function by adding new terms to equation (1).

3.2 Classification-Based Routing

Once components are laid out either by the simulated annealing algorithm or by manual placement, tubes must be routed between the components. This tool emulates the tubes generated by the human designers. Examination of existing units showed that many of the tubes bore a family resemblance to one another. It was noted that the tubes were distinguished by the fact that all changes in the vertical coordinate occurred parallel to the vertical- (or “Z-”) axis. These tubes are denoted “plane-orthogonal” tubes. In addition, the tubes could also be classified according to the number of bends they contained. Thus, a knowledge-based approach was taken using the object-oriented system ICAD.

The class of plane-orthogonal tubes encompasses all tubes that satisfy the following two conditions:

1. all straight segments lie in the horizontal (XY) plane or are parallel to the Z-axis;
2. all bends lie in the horizontal plane or in a plane that contains a line parallel to the Z-axis -- arbitrary bends are allowed in the horizontal XY plane but bends between a vertical segment and a segment in the XY plane must be 90 degree bends.

The definition of planes is made with respect to the horizontal base of the unit.

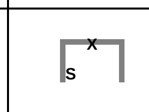
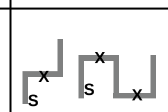
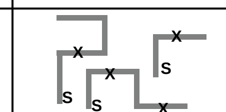
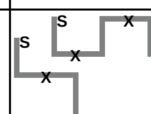
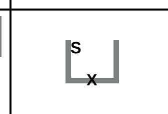
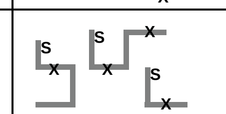
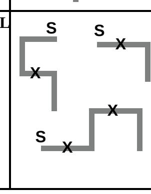
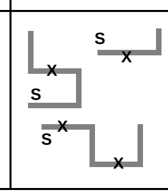
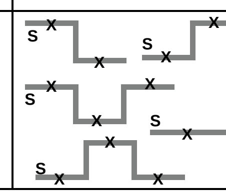
Historically, these tubes have been preferred for a number of reasons. Tubes cannot be designed in isolation; they must always be designed with reference to specific, oriented and positioned components within a unit. The unit fixes a frame of reference inside of which the designer must envision and draw the tube routes. Plane-orthogonal tubes are more easily envisioned and drawn in 2-D plan and elevation views of the unit than are arbitrary 3-D tubes using the 2D CAD systems commonly in use in industry. In addition there is a perception that these tubes are easier to measure and verify. For these and other reasons, analysis of existing units showed an evident preference for this class of tubes.

3.2.1 Plane-orthogonal Tube Families

Tubes connect one component to another via ports. As a simplification we can assume that all ports are one of three types: 1) up, 2) down, or 3) horizontal. Up and down ports are normal to the horizontal plane; horizontal ports lie in the horizontal plane. Most ports that are connected to components that are anchored to the unit meet these assumptions. Ports that are oriented at arbitrary angles are accounted for by following the port direction for the minimum distance required by manufacturing constraints and then bending into the closest of the three preferred port directions.

Since there are three possible directions for both the inlet and outlet ports there are a total of nine combinations in all. Families of plane-orthogonal tubes were derived by considering each of the combinations in turn. In general, the applicable tube types for a given port combination are determined by the port directions, the distance between the ports and the manufacturing constraints. Ports that are close together are more difficult to route than ports that are further apart because the physical capabilities of tube bending machines impose minimum lengths on straight segments and minimum radii for bends. To route tubes between points that can’t accommodate these minima it is necessary to use an indirect route to satisfy the constraints.

Table 1. Tube Family Primitives. View is in vertical plane. Start direction from row indicated by “S”; end direction from column. “X” indicates permissible bend in horizontal plane within current implementation.

END / START (S)	UP	DOWN	HORIZONTAL
UP			
DOWN			
HORIZONTAL			

The primitive tubes for the family of inlet and output port combinations are given in Table 1. The primitives are parametric in that the lengths of the straight segments and angles of the bends are variable. Further, by rotating a bend off a vertical segment, the tube can change direction within a horizontal plane. To form more complicated tubes using these primitives, a bend can be put in any straight segment within a horizontal plane. There is no upper bound on the length of a tube or the number of bends it might contain; however, in practice we limit the complexity of tube routes that are generated to no more than three horizontal runs and no more than five runs in all. Although recursive in theory, for this implementation only one in-plane bend is permitted per straight horizontal run from a primitive; this feasible bend is indicated by an “X” in table. For each port combination, then, there may be several candidate families of varying degrees of complexity. The significance of this is that if two ports are too close together such that the minimum straight run length cannot be satisfied, then more complicated tubes must be created to meet the required connection.

The class of plane-orthogonal tubes commonly found in HVAC equipment can be generated from this classification and generation strategy. Note that although arbitrary bends are permitted in-plane and orthogonal bends out-of-plane, there are still limitations imposed on how many bends are allowed. As well, these bend requirements restrict the effectiveness of the tube router; one or more arbitrary bends out-of-plane, or additional bends in-plane, could lead to shorter tubes or feasible solutions which are not generated by the algorithm.

3.2.2 Plane-Orthogonal Tube Routing Strategy

Plane-orthogonal tubes are routed using a generate-and-test strategy. Before the algorithm is invoked, a set of components that meets the performance criteria will have been identified, positioned, and oriented by the designer. The geometry of the components, their ports, and their positions and orientations are taken as inputs. In addition, the tube material, diameter, and the constraints imposed by the bending equipment are known. The strategy proceeds as follows:

1) The user requests tube routes to connect a given pair of ports;
2) The user controls the level of complexity of the generated tube candidates (*e.g.*, an upper limit on the number of bends is defined);
3) The system generates multiple candidate solutions within these specifications;
4) Solutions that interfere with the components are eliminated;
5) Potential solutions are presented to the user;
6) User browses candidate solutions;
7) User can accept a candidate as is or use it as the basis for modification;
8) User continues to generate sets of alternatives until satisfied that a sufficient number of alternatives have been explored or the complexity limit is reached.

Thus, the objective of the tube generation strategy is not a single tube that "solves" the routing problem for a pair of components but a set of candidate solutions that the user can explore and modify. Elaborate obstacle avoidance algorithms are not used because there is a good likelihood that there is at least one non-interfering tube candidate in the generated set. In cases where this is not true, or in cases where none of the plane-orthogonal routes is acceptable to the designer, the user asks the system to "try a little harder" by generating a route using the simulated annealing approach described next.

3.3 Non-Orthogonal Routing

The two primary drawbacks to traditional plane-orthogonal routing approaches are that they may not always generate a feasible route or may lead to unacceptable routing lengths or numbers of bends. There is a coupling between route length and number of bends, each of which is expensive. As the route leaves the plane, the traditional approach is limited to vertical and horizontal segments. Further, even within the plane, a limited number of bends and runs are admitted. Both of these restrictions lead to significantly longer run lengths, more bends, and possibly infeasible solutions.

Recall that out of every port, a straight segment of minimum length is required by the tube bending machines. The simplest non-orthogonal tube route would be a straight segment that connects the end of these straight segments. Although this tube is considered, it is usually infeasible in that it often penetrates a component or does not satisfy the minimum length requirement.

A general approach to non-orthogonal routing (*i.e.*, routing with arbitrary angles in all three dimensions) was developed to address these issues. Note that the plane-orthogonal knowledge-based system generates feasible, but not necessarily optimal, solutions. The non-orthogonal routing algorithm, however, takes an optimizing approach, extending the simulated annealing algorithm used for component placement.

To extend the simulated annealing algorithm, the move set and objective function must pertain to optimization of routing configurations rather than component configurations. The move set for the routing algorithm consists of four different types of moves that perturb a route: *add*, *remove*, *relocate* and *vector-relocate*. The first move adds a bend to a route at a random location and the second one deletes a bend at random. The relocate move changes the location of a bend by choosing a bend and moving it in a random direction. In contrast, vector-relocate moves a bend along the direction of one of the two route segments (chosen at random) that meet at that bend. The effect of the vector-relocate move is to change the length of one of the route segments that meet at a bend without changing its orientation (though the orientation of the other segment does change).

The objective function retains the form given by equation (1), but the terms in the objective function correspond to routing objectives and penalties. For routing optimization, the objective function has four terms. The first and second terms are the total length of all routes and the total number of bends in all routes in the design. The third term is a penalty for routes that intersect components. The fourth term is a penalty for straight segments that are too short to meet the manufacturing constraints from the tube bending machines. As before, feasible designs are generated as the optimization drives these penalties to zero. The non-orthogonal routing algorithm is presented in greater detail for general applications in (Szykman and Cagan, 1995b) and (Szykman, 1995).

The resulting algorithm generates tube routes where the plane-orthogonal knowledge-based system generated infeasible or expensive alternatives. Since a non-orthogonal route can include vertical out-of-plane segments and 90° bends, plane-orthogonal routes can be thought of a subset of general non-orthogonal routes; thus, the best non-orthogonal route will never be worse than the best plane-orthogonal route in terms of length or number of bends. However, as discussed above, plane-orthogonal tubes are often preferred by the designer, and thus within the total system, it is anticipated that the designer would generally use the non-orthogonal approach only for those tubes that are too difficult or costly to route in the traditional way.

The real cost of tubes routes is very much dependent on the position and orientation of the components and their ports. Although the non-orthogonal approach may be able to generate an acceptable route where the plane-orthogonal approach can not, a change in position of the components could lead to a much preferred route. Since the cost of the overall layout is heavily influenced by the routing costs, it would be preferable to take those costs into account during the placement of the components. A concurrent layout and routing approach has been explored as discussed in Szykman (1995).

4. EXAMPLE: HEAT PUMP LAYOUT

The simulated annealing-based component placement, knowledge-based plane-orthogonal tube routing, and simulated annealing-based tube routing algorithms will now be illustrated on the design of a typical heat pump. The problem consists of laying out the main components of the heat pump: the compressor (and its base), the accumulator, the reversing valve, the input and output valves to the coil (*i.e.*, heat exchanger), and the input and output (service) valves to the overall unit.

A number of constraints were used to define the layout problem. First, the reversing valve was fixed at the origin. Since only relative placement of components matters, any one of the components could be selected to be fixed. Also, none of the components were allowed to rotate; the orientation of the compressor, accumulator and reversing valve were fixed to preserve their vertical orientations, and rotations of the coil and service valve were forbidden to fix the direction from which tubes entered the valves.

Several relative location constraints that are characteristic of heat pump layout problems were also applied to the components:

- the coil ports and service valves were required to be to the right of the compressor, the accumulator and the reversing valve;
- the service valves were required to be on the same side of the heat pump container;
- the coil ports were constrained to have the same horizontal coordinates, with one valve being 100 mm above the other;
- the compressor was constrained to be on top of the compressor base and had the same horizontal coordinates;
- the bottoms of the compressor base and the accumulator rested on the same horizontal plane, representing the base of the heat pump container;
- the bottoms of the reversing valve, coil ports and service valves were constrained to be above the bottom of the compressor base, *i.e.*, above the base of the container.

In all, 27 constraints were applied to the components in addition to the ones used to fix the reversing valve.

Six tubes were then routed with endpoints as follows:

i. the top of the compressor to the top tube of the reversing valve;
ii. the side of the compressor to the top of the accumulator;
iii. the top of the accumulator to the bottom tube 2 of the reversing valve;
iv. the bottom tube 1 of the reversing valve to the side of coil port 1;
v. the bottom tube 3 of the reversing valve to the side of service valve 1;
vi. the side of coil port 2 to the side of service valve 2.

4.1 Results

To begin, the simulated annealing placement code (Section 3.1) was run alone to position the components. One set of results is shown in Figure 1. Note the dense packing of the components while satisfying the spatial relations specified. In this example, the concurrent placement and route approach was not run. Thus, there is no guarantee that the resulting layout is routable. Next the plane-orthogonal routing algorithm (Section 3.2) was used to generate a set of traditional plane-orthogonal tubes to the same layout. The routed solution is shown in Figure 1a; in this and subsequent illustrations the hidden lines of the tubes were not removed so as to allow the viewing of the tubes -- unless noted, none of the tubes that are shown intersect any components or each other. Although the tubes appear to be well routed, because the placement algorithm positioned the side of coil port 1 close to, and in line with, the accumulator, a traditional plane-orthogonal tube between the reversing valve and the side of coil port 1 (tube iv) was not feasible and could not be generated for that connection.

Next, annealed tube routes (Section 3.3) were generated for the same layout of components (Figure 1b). These routes may appear less organized, but in reality they are of lower cost (based on the objective function of length and number of bends) than the plane-orthogonal routes; of course additional criteria such as manufacturing and assemblability have not been considered. In Figure 2, the equivalent tubes from both codes are shown (in the same sequence). Note that the tubes between the top of the compressor and the top of the reversing valve in 2i are approximately the same shape from both approaches. Note also that the tube between the side of coil port 1 and the reversing valve that could not be generated with the plane-orthogonal approach is generated by the annealing code (Figure 2iv). However, the tube still does penetrate the accumulator; the annealing code did the best it could to bring the intersection penalty to zero but a tube could not physically connect the ports without violating the minimum straight length rule. In this case the design requires further tweaking by the designer for feasibility. The coil service values were moved 15 mm out to allow the tube iv sufficient space to fit.

The reality for the designer is that the plane-orthogonal routes may in general be preferred. However, for those tubes that are difficult or impossible to route with that approach, the annealing approach will be used. Figure 1c shows the same layout of the components with a routing that takes the "best" tubes from both approaches as determined by the designer.

One other way to get around the problem of difficult routes is to try a different layout, or for the designer to tweak the layout from the placement algorithm as was done in the example. Due to the expense of and constraints caused by tube routes, a concurrent placement and route is a promising alternative. The tube between the coil and accumulator in this example is an obvious motivation for such a technology. However, even with the current set of completed tools, the rapid computation time makes feasible the generation of multiple solutions for the designer's use. What is interesting in this example is that the final design shown in Figure 1c has a selection of routes from the two routing codes. Again, the system of tools is meant only to support the designer; it is the designer who makes the decisions on which layouts and tubes resulting from the various tools are accepted.

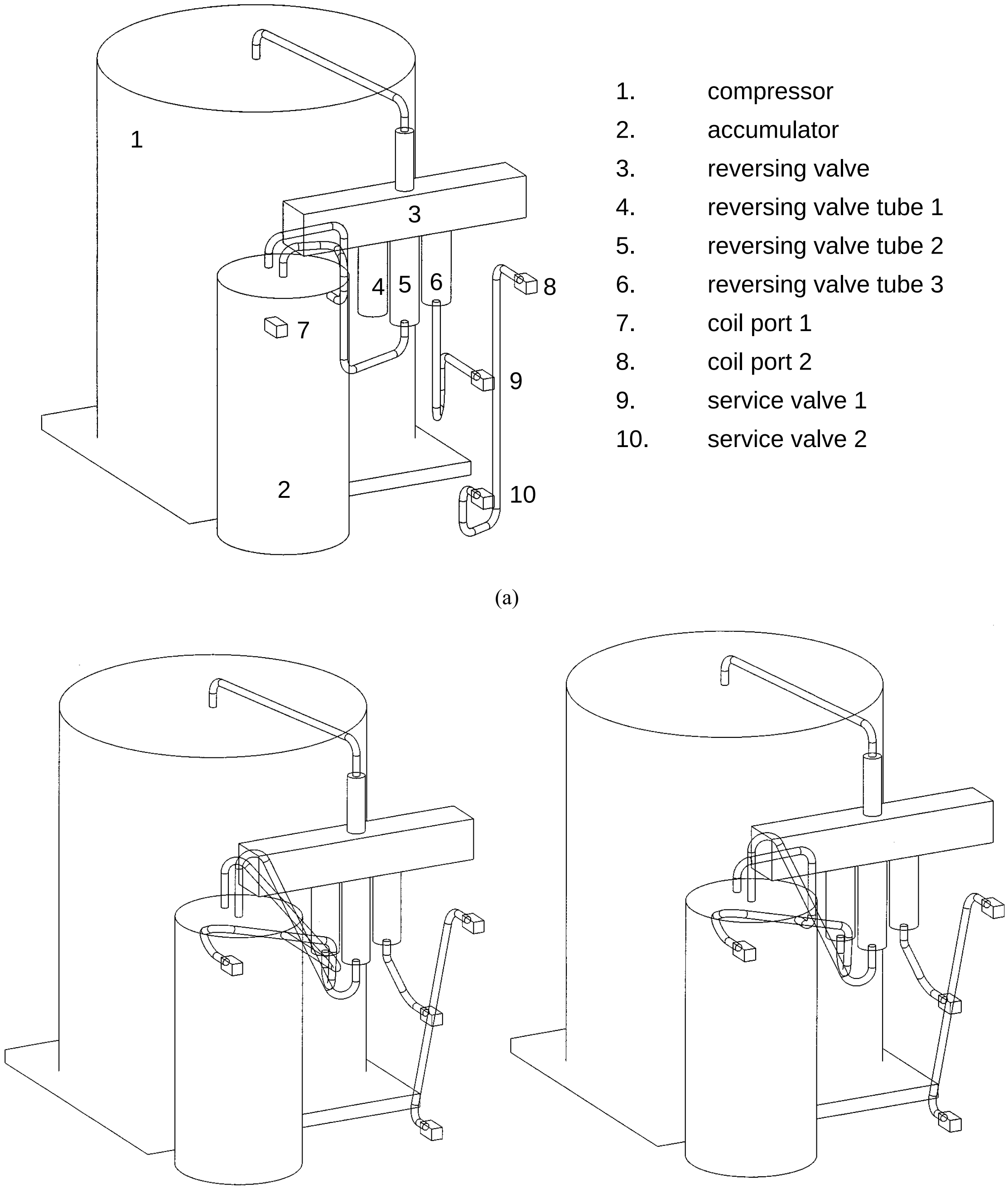


Figure 1. Simulated annealing placed components routed by a) classification-based tube routing algorithm, b) simulated annealing-based tube routing algorithm, c) the most desirable tubes from both approaches.

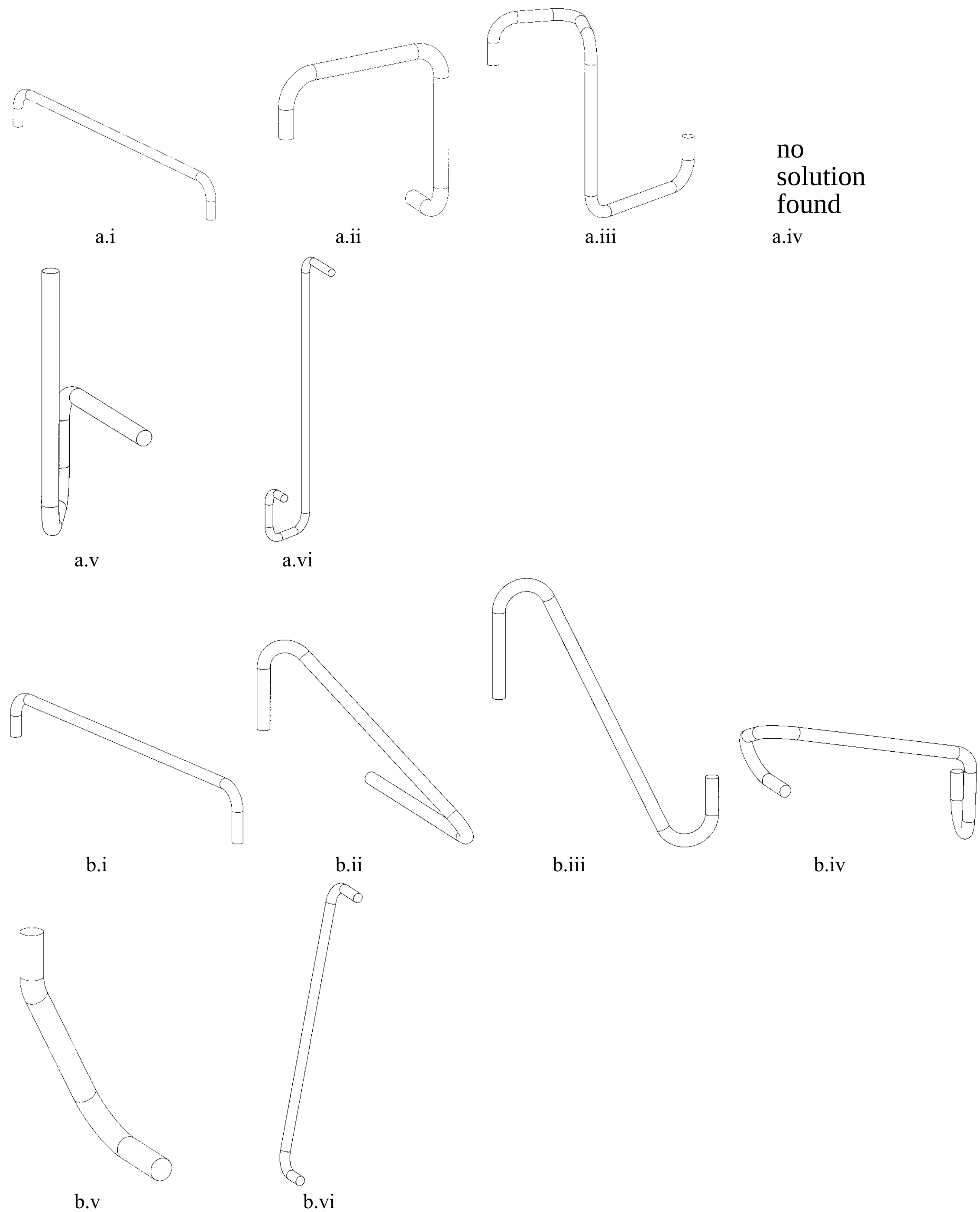


Figure 2. Tubes for layout of Figures 1: a) classification-based plane-orthogonal tubes and b) analogous simulated annealing-based tubes.

5. CONCLUDING REMARKS

A group of computer-assist design tools have been presented as a systems approach to the layout of HVAC systems. The design tools were the result of an industry-academia collaboration that recognized and utilized the unique capabilities and perspectives of each organization to pursue short-, mid-, and long-term technologies. Through the heat pump example, the advantages and disadvantages of each tool can be seen. The simulated annealing placement algorithm is able to quickly generate a variety of dense packings; however unless constraints such as accessibility are expressed, the resulting layouts may be difficult to route, requiring the designer to tweak the design further. The plane-orthogonal routing tool is able to generate traditional HVAC routes; although typical in the HVAC industry and straightforward to assemble, these routes can be long and have numerous bends, and some realistic routes may not be describable by the algorithm. In contrast, the simulated annealing router produces complex routes of minimum length and number of bends; however, these routes may be difficult to assemble and lack the perceived regularity of the plane-orthogonal routes. In practice the best routes from both approaches are selected by the designer within a system.

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