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METHODOLOGY FOR ENERGY EFFICIENT DESIGN OF COOLING PLANTS

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1. Introduction

Over the years, new requirements have continuously been set for the improvement of people's living and working conditions, which necessitates rational energy management. In such type of facility, the best possible working and living conditions need to be provided, subject to an optimal economic approach to energy distribution and consumption. Therefore, a cooling plant system must comply with all these requirements, primarily considering the characteristics and intended purpose of the facility and specifically ensuring that the plant's operation is adapted to the external conditions and internal requirements of the building (consumers) [Donjerković 1996].

Cooling plants, in particular those using water cooled chillers/ heat pumps, are very often used for the air conditioning of large commercial buildings, as well as industrial processes. From the investment viewpoint, they may constitute substantially greater investments requiring more space to accommodate them and energy and higher maintenance and energy costs. Irrespective of this, they have numerous advantages compared to, for example, split systems, including significantly higher energy efficiency, better manageability of the plant, and a longer service life. Such higher energy efficiency is particularly noticeable, while the system under a partial load [Energy Design Resources 2010]. Energy consumption in buildings is always the main concern and thus receives plenty of attention in research efforts. Of course, the more complex a building is, the greater is the need to develop new approaches to the optimization of energy use [Wang et al. 2015]. In addition to the general definition of energy efficiency, being the degree of using energy for the purpose of obtaining an effective output [Albers et al. 2014]. Also many other definitions of energy efficiency can be found in literature [Niemann et al. 2009]. During the product development process, there are also many developed guidelines and tools that help achieve a more energy efficient product [Rath et al. 2011]. Energy efficiency is achieved by adequately defining the customer's or investor's requirements at the very beginning of the system development process [Rath et al. 2012]. It is of great importance in businesses today because, while searching for new knowledge, there is a need for comprehensive and effective methods and tools that will help the designer integrate the energy aspects during the designing process (ec. [Brezet 1997], [Bonvoisin 2010], [Rath et al. 2011]). On the other hand, the current methods, tools and guidelines are not acceptable as such for resolving specific problems, namely the cooling plant contemplated in this research. Therefore, it is always necessary to develop new methodologies, such as the ones presented in this paper. It is important to underline that the authors' work presented in this paper was based exclusively system verification based on the efficiency associated with the amount of electrical energy used and the system performance and the resulting plant cost.

The research presented in this article describes the development of a methodology for new complex technical systems ([Hubka and Eder 1988, 1992], [Lindemann et al. 2009]), cooling plants. The

methodology presents all its steps and an evaluation analysis aimed at obtaining optimal system architecture. The technical system was evaluated in relation to energy efficiency and electrical energy savings. Of course, it is possible to reverse to the initial steps of the methodology (customer requirements and equipment selection) for the purpose of changing certain subsystems and obtaining a satisfactory solution (optimum system architecture according to energy efficiency).
The following Chapter describes a brief review on related work of some of the methodologies for developing product variants, tools and evaluation of thus obtained solutions. There was also a brief comparison of the methodology proposed in this paper with those mentioned methodologies. Chapter 3 present the author's motivation for conducting this research, while Chapter 4 briefly describes the methodology on a step-by-step basis. Chapter 5 provides a verification of the methodology on a case study of a cooling plant in the pharmaceutical industry. A discussion of the results obtained from the case study is provided in Chapter 6. Chapter 7 closes the paper and provides a conclusion derived from the research, as well as potential directions of future research.

2. Related work

As the presented methodology described in the paper includes the selection of product variants and their evaluation with regard to energy efficiency, cost, and product performance with the use of existing computer software from manufacturers, the literature review is necessary to give an overview of several point. Below is a brief overview on related literature of the existing methodologies, approaches, methods and tools, whose purposes are contained in the presented methodology.
First it is important to mention a series of structured methodologies Design for Variety (DfV), which is develop to help design teams reduce the impact of variety on the life-cycle costs of a product [Martin and Ishii 1996, 1997]. It is also listed some other methodologies from this field. For example [Galsworth 1994] describes the variety effectiveness program (VEP), a methodology to help companies decrease the complexity of variety. Fujita et al. [1998] used optimization techniques to
estimate the best architecture for a family of aircraft, while Tseng and Jiao [1998], developed the product family architecture model (PFA model) to handle the tradeoffs between diversity of customer requirements and reusability of design and process capabilities. Nayak et al. [2000] present a Variation-Based Platform Design Methodology (VBPDM), which aims to satisfy a range of performance requirements using the smallest variation of the product designs in the family. Claesson et al. [2001] modeled product platforms using configurable components. Pedersen et al. [2013], present a systematic domain-independent engineering approach to design hierarchical product platforms based on similarity or commonality within complex engineering systems. Second we mention some methodologies for evaluation and validation of product variants. Lechener et al. [2011] develop of a model-based evaluation approach of variant-driven complexity in the automotive industry by capturing relevant product variety driven costs and performance impacts. Evaluation of product families due to their complexity is desribed in methodology given by [Rissanen et al. 2012]. Also there is some methodologies based on Design for Experiments (DoE), like validation process for complex products [Kortler et al. 2012]. Also it is need to mention about tools for seelction of products. Some tools for supporting selection of configurable products and avoiding iteration caused by wrong product selections has been most directly addressed by [Pargamin 2002]. There are many models and tools that support product selection of off-the-shelf products, analyzed, described in literature like by [Stolze 1999] and [Ardissono et al. 2002]. The mechanisms for supporting product selection analytically can be divided into filtering, visualization and evaluation mechanisms [Stolze 1999]. Heiskala et al. [2003] describe a practical web-based tool called CCP (Comparison of Configurable Products) that extends analytical product selection to configurable products.
The methodology is primarily developed on authors' experience through many years and it shown how it is really work in industry. The need for develop something like that is very large, because in industrial section in Croatia, there are many companies engaged in the same or similar problems.

3. Motivation

In the process of designing the cooling plant system (during the decision-making process [Simon 1960]), the designers were put in a position where they define problems and arguments in a specific phase of

collecting information and knowledge primarily based on their own and other persons' experience, and also define how to design a particular plant system. Of course, this may also result in uncertainties at the time the best proposed design is to be decided. Inexperienced and experienced designers should be distinguished between with respect to how they approach the resolution of a designing problem. It has been noticed that inexperienced designers are more likely to use the trial and error method until such time the result becomes satisfactory. Unlike them, more experienced designers evaluate their decisions before applying them, mostly based on experience, and thus avoid multiple repetitions. To avoid or at least reduce the possibility of inadequately defining problems and arguments, it is necessary to examine the possibility of applying and developing new methodologies and system architectures based on existing information and knowledge of the problem concerned gained from experience, and of modifying and applying them to the designing problem concerned.
After the authors have reviewed the current situation with respect to designing a cooling plant system over a number of years, they reached the conclusion that problems exist, mostly in connection with: the defining and recording of design solutions and problems, the defining of arguments leading to decisions to propose alternatives and selection of one or several proposed alternatives to the solution, the linking of specific designing problems, and especially the lack of quality engineering literature in the area concerned. The authors were thereby motivated to provide a proposal to help find solutions in design offices more quickly, and especially to help inexperienced designers prepare their future designs in connection with the designing of cooling plant systems.

4. Description of the methodology

The methodology used for the development of cooling plant architectures is presented in the flowchart in Figure 1 and includes 4 basic steps. Obviously, the solution is of an iterative nature, which means that several steps need to be undertaken to obtain the desired optimum cooling plant architecture. It is important to note that the authors' work presented in this paper was based on equipment supplied by manufacturers with whom they normally deal in the company, including using such manufacturers' software. The methodology was created by using such software, but is, of course, applicable to other manufacturers as well.
Listed below are the steps of the methodology and their brief descriptions are provided:
1. Defining the customer (investor) needs and engineering requirements [Otto and Wood 2000] – the initial step of the methodology. It begins with a discussion with the customers (investors), where their needs are defined (e.g. the intended purpose of the plant, the location of the plant, the consumer circles including data about specific cooling loads, operation of the plant during the year, etc.). Based on such customer requirements, the engineering requirements are determined (e.g. cooling plant's modes of operation, types of equipment, chiller/ heat pump operating principles, permitted levels of sound pressure, etc.).
2. Selecting different items of equipment in the cooling plant – based on the information obtained in the preceding step, specific items of cooling plant equipment are now selected. In addition, the system is set using the basic data available in the manufacturers' catalogues, as well as their software (product configurators). It is possible to define several solution variants when selecting a specific type of equipment. In that case, the device that has better performance (technical characteristics) and lower cost will be selected. Equipment is selected in the following order, i.e. it includes several sub-steps:
a) Selecting the chillers/ heat pumps – the types and number of chillers/ heat pumps are selected [TRANE 1999a, 1999b, 2000b, 2001] according to the information obtained about the total cooling load (calculaed or obtained), temperature regimes on the evaporator and condenser sides of the device, the working fluid and refrigerant to be used by them, the type of condensers, place of installation (outdoor or indoor), the sound pressure levels, and the energy class of the device (as well as information about the minimum values of the Energy Efficiency Ratio (EER), European seasonal energy efficiency ratio (ESEER) and Coefficient of performance (COP) parameters [Saheb et al. 2006] and the location of the device – depends on the architecture solution of the cooling plant space and regarding to that the maximum device dimensions depend on them). Therefore there are different variants of the device performance - with air-cooled condenser and water cooled condenser. Devices with water cooled condensers are certainly more expensive, but funds invested in them returning after a few years. Also

from the standpoint of the energy efficiency of the device are much more favorable solutions. On the other side devices with air-cooled condenser typically used for smaller cooling / heating capacities. Manufacturers product catalogue together with TRANE's Iris ® and TOPSS ® configurators were used for the selection of chillers.

b) Selecting the cooling towers – the types and number of cooling towers are selected based on the information about the selected chillers/ heat pumps (total cooling load installed and transmitted electric powers of the devices) [Donjerković 1996], [Recknagel et al. 2012], subject, of course, to defining the temperature regime on the condenser side of working fluid and the ambient temperature. Manufacturers product catalogue together with DECSA's DECSA Selection Tool ® configurator was used for the selection of cooling towers.

c) Selecting the dry coolers (optional) – dry coolers with an option of so-called "free cooling" mode [Donjerković 1996] are selected to allow the cooling plant to operate in the winter regime and sometimes in some parts of transitional regimes. To select them, we need to know the number of consumers that will operate in such modes and their cooling load, as well as the transmitted electric power in such case, and need to define the working fluid temperature regime and the ambient temperature below which we expect the devices to operate. Sometimes it is necessary to perform energy analysis of the system with the aim of optimizing their operation. The analysis can show us where the temperature regime is justified to use free cooling mode with the goal of better energy efficiency of the overall system. Manufacturers product catalogue together with REFRION's REFRION Selector ® configurator was used for the selection of dry coolers.

d) Selecting the circulating pumps on the condenser and evaporator sides of the cooling plant [Donjerković 1996], [Menon and Menon 2010], [Recknagel et al. 2012] – condenser and evaporator pumps are determined on the basis of the defined temperature regimes, working fluids and the flow of working fluid on the condenser and evaporator sides. Before that, it is necessary to calculate the pressure drops in each branch of the pipeline, for which we used the "Pipe Flow Expert" software. The number of circulating pumps is determined on the basis of the type of consumer and consequently, the flow volume of the working fluid, as well as the calculated pressure drops in each pipeline branch. Sometimes we have more selected chillers / heat pumps in system. Depending on the regime, it is not always a case that all energy sources operate with full capacity. In this case, as a recommendation, in selection of one circulation pump, it should meet with regard to flow through the chiller/ heat pump with the largest cooling capacity, depending also on the device side to which it is applied. The selection always includes a spare (passive) pump. In addition to the pumps, the type of frequency converter is also defined in case of variable volume flow. Manufacturers product catalogue together with GRUNDFOS's WinCAPS ® configurator was used for the selection of circulating pumps.

d) Pipeline dimensioning – after selecting all required mechanical equipment and placing it in the designated area within the plant, the pipeline is dimensioned according to the specified working fluid flow rates and pressure drops [Recknagel et al. 2012]. During that, as a criterion is check airflow speed, to be within certain limits.The "Pipe Flow Expert" software ® is used for this purpose.

e) Selecting the armature and measuring and controlling equipment – we use ARI Armaturen's ARI - myValve Calculator ® (ball valves, check valves, butterfly valves, strainers, etc.) and IMI Hydronic Engineering's HySelect software ® (selection and sizing of the balance valves) (product configurators) to select the armature, and SIEMENS's SIEMENS Simple Select ® and HIT Tool software ® (product configurators) to select the measuring and controlling equipment (motor drives, temperature sensors, pressure sensors, etc.).

3. Evaluation analysis – an iterative analysis was performed for the proposed system architecture variants through the respective iteration steps. It is based on calculating the total electrical energy consumption in 1 year for each proposed system variant. For this calculation, we need the amount of electrical energy used in 1 year for each of the consumers and the overall price of electrical energy consumption in 1 year [kWh], according to which we select optimal cooling plant architecture. In this process, it is necessary to define the weighting coefficients according to the type of the consumers and their operation regimes during the year, i.e. the share of each partial or full system load. With this in equioment selection, a a criterion is check device performance, as well as the cost price.

4. Changes to needs/ requirements and/ or equipment selection - as mentioned above, the methodology is of an iterative nature, which means that changes may be made to customer requirements and equipment selection based on feedback, and then a repeated evaluation analysis is to be performed to obtain optimal cooling plant system architecture with respect to energy efficiency/electrical energy consumption.

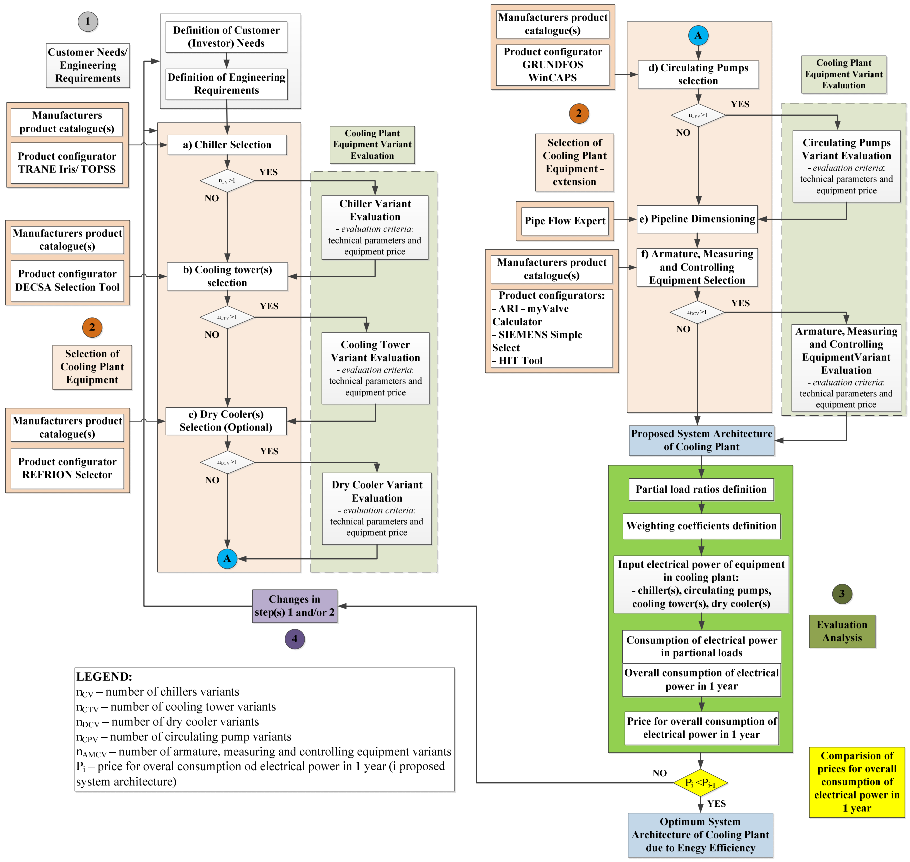

Figure 1. Representation of proposed methodology - flow diagram

5. Case study - cooling plant with water based chillers

To verify the previously described methodology, a case study of a complex technical system, a cooling plant [Donjerković 1996], [Recknagel et al. 2012] with water based chillers in the pharmaceutical industry, was selected. The authors often encounter a similar type of system in their activities in daily work in industry, so their experience in designing such systems was of great help in this research.
Generally, the system comprises the following subsystems: a cooling energy source (a chiller or several of them), the condenser part of the cooling plant (a cooling tower of several of them, a dry cooler or several of them, condenser pumps, armature, measuring elements and the associated pipelines), the evaporator part of the cooling plant (evaporator pumps, armature, measuring elements and the associated pipelines), and automated control of the plant.

5.1 Customer beeds/engineering requirements

The selection of the cooling plant equipment and proposal of the cooling plant system's initial architecture were based on the requirements set by the customers needs and the engineering requirements derived therefrom.
The customer needs were as follows:

- The plant must be located in the northern part of the Republic of Croatia;

- The plant must be designed for indoor installation with water based chillers, provided that the cooling towers and dry coolers are located outside the facility;
- The plant must be able to operate in variable external conditions (winter/summer and transitional regime modes);
- The plant is designed for industrial cooling processes, as well as for comfortable air conditioning in the pharmaceutical industry,
- Silent operation of the plant must be ensured; and
- The plant must feature automated control.

The engineering requirements are as follows:

- The cooling plant must be able to operate all day (24 hours), every day of the year (365 days);
- A free cooling mode must be ensured in the winter mode and during the transitional period;
- When selecting the chillers, it must be ensured that they operate using permitted refrigerants;
- An appropriate number of chillers will be selected according to the defined cooling load, type of consumers and the time of their operation (in a particular regime mode);
- When selecting the chillers, the permitted levels of sound pressure under the national regulations defining the types of working areas must be taken into account;
- The chillers/ heat pumps must be able to operate in a parallel work;
- The plant must have uninterruptible power supply of 3x380 V, 50 Hz;
- The temperature regime of cooled water on evaporator side is 6/12 °C; and
- The temperature regime of cooling water on condenser side is 29/35 °C.

5.2 Selection of cooling plant equipment

The selection of equipment was proceeded with according to the total defined cooling load of the consumers in the facility. In this case, it was approximately 6500 kW. As this is a relatively high load, for this purpose three water based chillers were selected: two with a centrifugal compressor and one with a screw compressor [TRANE 2000b]. The case study shows that the selected chillers are manufactured by TRANE ®, cooling towers are manufactured by DECSA ®, and the dry cooler is manufactured by REFRION ®, while the circulating pumps are manufactured by GRUNDFOS ®. We selected the equipment by using the manufacturer's software (product configurators) based on a product catalog (like it is described under section 4).

As shown, two variants of the solution were proposed: Variant 1 with a CVHH type centrifugal chiller using the new HFO-1233zd (E) refrigerant, and Variant 2 with a CVGF type centrifugal chiller using R134a [TRANE 1999b], [Hanson et al. 2009]. Both variants propose the same water cooled cooling chiller with a screw compressor, type RTHD (see Tables 1 and 2). In addition to the selected type of chiller and its cooling load, the Tables also present the basic technical characteristics of the chillers on their evaporator and condenser side, the input power and the EER and ESEER energy efficiency parameters [Hanson et al. 2009]. These parameters indicate that these are energy class "A" devices (according to Eurovent standard), which will ensure maximum electrical energy. The presented data was obtained by using product catalogues [TRANE 1999a, 1999b, 2000b, 2001] and TRANE's TOPSS software ® (product configurator).

Table 1. Chiller selection - variant 1

CHILLERS - VARIANT 1													
Label	Manufacturer/ Model	Refrigerant	Cooling capacity	Evaporator - technical data			Condenser - technical data			Input electrical power	Voltage/ number of phases/ frequency	Energy efficiency	
				Cooling water temperature		Water volume flow	Cooling water temperature		Water volume flow			EER	ESEER
		Label	Q [kW]	T_u [°C]	T_i [°C]	V_{HV} [m^3/h]	T_u [°C]	T_i [°C]	V_{RV} [m^3/h]	N [kW]	U [V]/ number of phases [-]/ f [Hz]	100%	
RV-1	TRANE CVHH 900	HFO-1233zd(E)	2800	12	6	398,5	29	35	474	483,2	400 / 3 / 50	5,79	8,91
RV-2	TRANE CVHH 900	HFO-1233zd(E)	2800	12	6	398,5	29	35	474	483,2	400 / 3 / 50	5,79	8,91
RV-3	TRANE RTHD 425 HSE	R134a	1430	12	6	203,9	29	35	235	240,3	400 / 3 / 50	5,95	8,77
	Sum		7030			1000,9			1183	1206,7			

After selecting the chillers, DECSA ® cooling towers and REFRION ® dry cooler were selected (see Tables 3 and 4). The cooling towers were selected according to the total load of the chillers (the sum of installed cooling load and electric power), while the dry cooler was selected according to the total load for those consumers that will need to be cooled in the winter and transition regime mode (also taking into account the cooling load and the total electric power required under such load). With manufacturers product catalogues, the software (product configurators) used for this purpose is the DECSA Selection Tool ® and the REFRION Selector ®.

Table 2. Chiller selection - variant 2

CHILLERS - VARIANT 2													
Label	Manufacturer/ Model	Refrigerant	Cooling capacity	Evaporator - technical data			Condenser - technical data			Input electrical power	Voltage/ number of phases/ frequency	Energy efficiency	
				Cooling water temperature		Water volume flow	Cooling water temperature		Water volume flow			EER	ESEER
		Label	Q [kW]	T_u [°C]	T_i [°C]	V_{HV} [m^3/h]	T_u [°C]	T_i [°C]	V_{RV} [m^3/h]	N [kW]	U [V]/ number of phases [-]/ f [Hz]	100%	
RV-1	TRANE CVGF 650	R134a	2540	12	6	362,8	29	35	427	431	400 / 3 / 50	5,90	6,40
RV-2	TRANE CVGF 650	R134a	2540	12	6	362,8	29	35	427	431	400 / 3 / 50	5,90	6,40
RV-3	TRANE RTHD 425 HSE	R134a	1430	12	6	203,8	29	35	234	240,3	400 / 3 / 50	5,95	8,77
	Sum		6510			929,4			1088	1102,3			

Table 3. Cooling towers selection

COOLING TOWERS													
Label	Manufacturer/ Model	Technical data									Frequency inverter		
		Heat rejection capacity	Wet bulb temperature	Cooling water temperature		Water volume flow	Number of fans	Air volume flow	Input electrical power	Voltage/ number of phases/ frequency	Manufacturer/ Model		piece
		Q [kW]	T_{vl} [°C]	T_U [°C]	T_I [°C]	V_{RV} [m^3/h]	n_f [-]	V_z [m^3/s]	N [kW]	U [V]/ number of phases [-]/ f [Hz]			
RT-1	DECSA TMA 34-537	4740	24	35	29	679,2	3	100,80	3 x 18,5	400 / 3 / 50	DANFOSS	FC-102P18KT	3
RT-2	DECSA TMA 34-537	4740	24	35	29	679,2	3	100,80	3 x 18,5	400 / 3 / 50	DANFOSS	FC-102P18KT	3
	Sum	9480				1358,4			111				

Table 4. Dry coolers selection

DRY COOLER										
Label	Manufacturer/ Model	Technical data								
		Capacity	Cooling water temperature		Ambient temperature	Water volume flow	Number of fans	Air volume flow	Input electrical power	Voltage/ number of phases/ frequency
		Q [kW]	T_U [°C]	T_I [°C]	T_a [°C]	V_{RV} [m^3/h]	n_f [-]	V_z [m^3/h]	N [kW]	U [V]/ number of phases [-]/ f [Hz]
SH	REFRION EA4D 2580-6/2	540	12	6	0	87,1	2x5	188.700,00	10 x 1,95	400 / 3 / 50
	Sum	540				87,1			19,5	

The selection of these devices was followed by the selection of the circulating pump types on the condenser and evaporator sides of the chillers. The "Pipe Flow Expert" software ® was used for this purpose.

According to the defined volume flows, pressure drops, workin fluids and temperature regimes, the electronically controlled circulating pumps were selected by using product catalogue [GRUNDFOS 2012] and GRUNDFOS's WinCAPS software ® (product configurator).

The pumps were selected by choosing for each side (condenser and evaporator) three operating pumps and one reserve pump with a parallel connection (see Tables 5 and 6). Tables present the basic data about the pumps: manufacturer, pump model, technical characteristics, input electrical power, voltage with number of phases and frequency, nominal pressure and frequency converter model.

Table 5. Circulating pumps selection - condenser side

CIRCULATION PUMPS - CONDENSER SIDE (29/35°C)										
Label		Pump manufacturer	Pump model	Technical data for circulation pumps		Input electrical power	Voltage /number of phases/ frequency	Nominal pressure	Frequency inverter	
				Volume flow	Pressure drop				Manufacturer	Model
				V_{HV} [m^3/h]	Δp [kPa]	N (kW)	U [V]/ number of phases [-]/ f [Hz]	PN [bar]		
C-1	Working pumps	GRUNDFOS	TP 200-270/4	374	245	45	400 / 3 / 50	16	GRUNDFOS	CUE 3x380-500V IP55 45 kW
C-2	Working pumps	GRUNDFOS	TP 200-270/4	374	245	45	400 / 3 / 50	16	GRUNDFOS	CUE 3x380-500V IP55 45 kW
C-3	Working pumps	GRUNDFOS	TP 200-270/4	374	245	45	400 / 3 / 50	16	GRUNDFOS	CUE 3x380-500V IP55 45 kW
	Sum			1122	245	135				
C-4	Reserve pump	GRUNDFOS	TP 200-270/4	374	245	45	400 / 3 / 50	16	GRUNDFOS	CUE 3x380-500V IP55 45 kW

5.3 Proposed system architecture

However, a system architecture proposal needed to be provided to determine the pumps of the evaporator side for subsequent analysis. For this purpose, two architectures were proposed through two iteration steps (as shows in Figures 2 and 3). The first system architecture shows (see Figure 2) the evaporator side of the cooling plant with constant volume flow through the primary circle and variable flows through consumer secondary circles. The primary and secondary circles are mutually separated by a hydraulic switch intended for balancing the system [Donjerković 1996]. The circulating pumps were selected accordingly (see Tables 6 and 7).

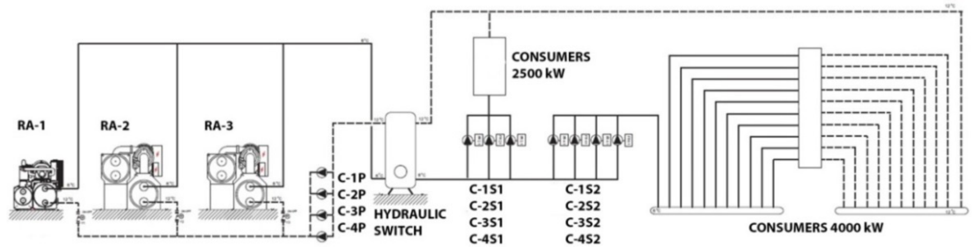

Figure 2. System architecture - iteration step 1

Table 6 shows the circulating pumps selected for the evaporator side of the chillers (temperature regime 6/12°C) for the primary circle with constant volume flow through them.

Table 6. Circulating pumps selection - evaporator side (primary circle) – system architecture 1

CIRCULATION PUMPS - PRIMARY CIRCLE - EVAPORATOR SIDE (6/12°C)								
Label		Pump manufacturer	Pump model	Technical data for circulation pumps		Input electrical power	Voltage /number of phases/ frequency	Nominal pressure
				Volume flow	Pressure drop			
				V_{HV} [m³/h]	Δp [kPa]	N [kW]	U [V]/ number of phases [-]/ f [Hz]	PN [bar]
C-1P	Working pumps	GRUNDFOS	TP 200-400/4	313	345	55	400 / 3 / 50	16
C-2P	Working pumps	GRUNDFOS	TP 200-400/4	313	345	55	400 / 3 / 50	16
C-3P	Working pumps	GRUNDFOS	TP 200-400/4	313	345	55	400 / 3 / 50	16
	Sum			939	345	165		
C-4P	Reserve pump	GRUNDFOS	TP 200-400/4	313	345	55	400 / 3 / 50	16

On the other hand, Table 7 presents the selected circulation pumps with frequency converters for the evaporator side of the chillers (temperature regime 6/12°C) for consumer secondary circles (consumer circle 1 – cooling load of approximately 2500 kW, and consumer circle 2 – cooling load of approximately 4000 kW) with variable volume flow through them.

Table 7. Circulating pumps selection - evaporator side (secondary circle) - system architecture 1

CIRCULATION PUMPS - SECUNDARY CIRCLE - EVAPORATOR SIDE (29/35°C)										
Label		Pump manufacturer	Pump model	Technical data for circulation pumps		Input electrical power	Voltage /number of phases/ frequency	Nominal pressure	Frequency inverter	
				Volume flow	Pressure drop				Manufacturer	Model
				V_{HV} [m³/h]	Δp [kPa]	N (kW)	U [V]/ number of phases [-]/ f [Hz]	PN [bar]		
		CONSUMERS 1 - 2500 kW								
C-1S1	Working pumps	GRUNDFOS	TP 150-260/4	180	240	18,5	400 / 3 / 50	16	GRUNDFOS	CUE 3x380-500V IP55 18,5 kW
C-2S2	Working pumps	GRUNDFOS	TP 150-260/4	180	240	18,5	400 / 3 / 50	16	GRUNDFOS	CUE 3x380-500V IP55 18,5 kW
C-3S1	Working pumps	GRUNDFOS	TP 150-260/4	180	240	18,5	400 / 3 / 50	16	GRUNDFOS	CUE 3x380-500V IP55 18,5 kW
	Sum			540	240	55,5				
C-4S1	Reserve pump	GRUNDFOS	TP 150-260/4	180	240	18,5	400 / 3 / 50	16	GRUNDFOS	CUE 3x380-500V IP55 18,5 kW
		CONSUMERS 2 - 4000 kW								
C-1S2	Working pumps	GRUNDFOS	TP 150-260/4	190	232	18,5	400 / 3 / 50	16	GRUNDFOS	CUE 3x380-500V IP55 18,5 kW
C-2S2	Working pumps	GRUNDFOS	TP 150-260/4	190	232	18,5	400 / 3 / 50	16	GRUNDFOS	CUE 3x380-500V IP55 18,5 kW
C-3S2	Working pumps	GRUNDFOS	TP 150-260/4	190	232	18,5	400 / 3 / 50	16	GRUNDFOS	CUE 3x380-500V IP55 18,5 kW
	Sum			570	232	55,5				
C-4S2	Reserve pump	GRUNDFOS	TP 150-260/4	190	232	18,5	400 / 3 / 50	16	GRUNDFOS	CUE 3x380-500V IP55 18,5 kW

Iteration step 2 proposes a system architecture (see Figure 3) using circulating pumps with variable flow in the primary circle. This eliminated the need for circulating pumps in the secondary circle and thus reduced the space needed for the equipment in the cooling plant. In addition, we need less electrical wiring for this equipment.

According to this architecture, we selected circulating pumps with frequency converters in the chiller's evaporator circle as presented in Table 8.
After all this steps pipeline dimensioning and the armature with measuring and controlling equipment selection.

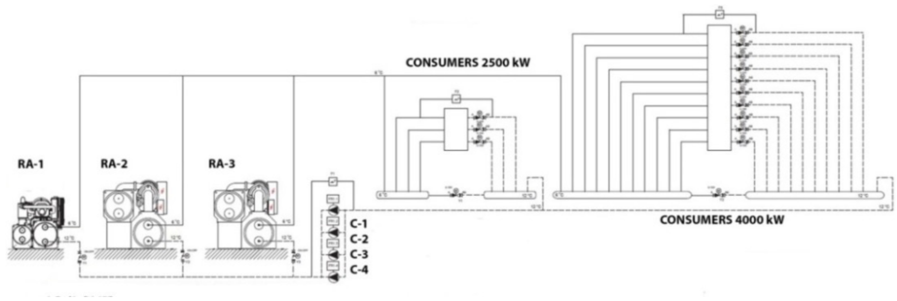

Figure 3. System architecture - iteration step 2

Table 8. Circulating pumps selection - evaporator side - system architecture 2

CIRCULATION PUMPS - EVAPORATOR SIDE (6/12°C)										
Label		Pump manufacturer	Pump model	Technical data for circulation pumps: Volume flow	Technical data for circulation pumps: Pressure drop	Input electrical power	Voltage /number of phases/ frequency	Nominal pressure	Frequency inverter: Manufacturer	Frequency inverter: Model
				V_{HV} [m^3/h]	Δp [kPa]	N [kW]	U [V]/ number of phases [-]/ f [Hz]	PN [bar]		
C-1	Working pumps	GRUNDFOS	TP 150-660/4	343	588	75	400 / 3 / 50	16	GRUNDFOS	CUE 3x380-500V IP55 75kW
C-2		GRUNDFOS	TP 150-660/4	343	588	75	400 / 3 / 50	16	GRUNDFOS	CUE 3x380-500V IP55 75kW
C-3		GRUNDFOS	TP 150-660/4	343	588	75	400 / 3 / 50	16	GRUNDFOS	CUE 3x380-500V IP55 75kW
	Sum			1029	588	225				
C-4	Reserve pump	GRUNDFOS	TP 150-660/4	343	588	75	400 / 3 / 50	16	GRUNDFOS	CUE 3x380-500V IP55 75kW

5.4 Evaluation of the proposed system architectures

Based on the system architectures proposed in iteration steps 1 and 2, we proceeded with the evaluation process.
For this purpose, we first performed an analysis of electrical energy consumption for the cooling plant with constant flows through the primary circle and consumer secondary circles to allow for a comparison with further analyses (see Table 9).
It should be underlined at this point that no analysis was performed for the condenser part of the cooling plant as its energy consumption is insignificant compared to the consumption of the evaporator part. In this case study, the architecture of this part of the system is the same for all iteration steps. However, this is not necessarily always the case.
As shown, the analysis was performed as follows and this principle was later used in other analyses for iteration steps 1 and 2. According to the ESEER parameters, partial system loads (at 25%, 50% and 75% loads) and full load of the system of 100%, we estimated the weighting coefficient (in %) which indicates how much time of the entire system's operation is used for operation under different loads.

Table 9. Evaluation analysis – cooling plant – evaporator side (constant volume flow through primary and secondary circles)

ESEER parameters				
Partial load ratio [%]	Weighting coefficient [%]	Working time [h]	Input electrical power for circulating pumps N[kW]	Consumption of electrical power [kWh]
100	3	262,8	257,5	67671
75	33	2890,8	184	531907,2
50	41	3591,6	165,5	594409,8
25	23	2014,8	92	185361,6
	Working time in 1 year [h]	8760	Overall consumption of electrical power in 1 year [kWh]	**1379349,6**
			Price for overall consumption of electrical power in 1 year [HRK]	**965.544,72**

This essentially depends on the abovementioned types of consumers and their modes during the year. As the cooling plant operates on a year-round basis, 24 hours a day, the number of operating hours was determined on the basis of the weighting coefficient, its total sum to equal 8760 hours (365 days a year times 24 hours a day). Based on such system load, we calculated the required electric power for the circulating pumps, and then the electrical energy consumption for each system load. Finally, we calculated the total cost of electrical energy in one year (in the national currency of the Republic of Croatia Croatian Kuna identified as HRK).
An evaluation analysis was similarly performed for the proposed system architectures in iteration steps 1 and 2 (see Tables 10 a and b).

Table 10. Evaluation analysis – cooling plant – evaporator side
a) - constant volume flow through primary and variable volume flow through secondary circles
b) - variable volume flow through primary circle

ESEER parameters				
Partial load ratio [%]	Weighting coefficient [%]	Working time [h]	Input electrical power for circulating pumps N[kW]	Consumption of electrical power [kWh]
100	3	262,8	244,84	64343,95
75	33	2890,8	181,12	523581,70
50	41	3591,6	163,11	585825,88
25	23	2014,8	81,57	164347,24
	Working time in 1 year [h]	8760	Overall consumption of electrical power in 1 year [kWh]	**1338098,76**
			Price for overall consumption of electrical power in 1 year [HRK]	**936.669,13**

a)

ESEER parameters				
Partial load ratio [%]	Weighting coefficient [%]	Working time [h]	Input electrical power for circulating pumps N[kW]	Consumption of electrical power [kWh]
100	3	262,8	197,8	51981,84
75	33	2890,8	128,5	371467,80
50	41	3591,6	76,71	275511,64
25	23	2014,8	31,64	63748,27
	Working time in 1 year [h]	8760	Overall consumption of electrical power in 1 year [kWh]	**762709,55**
			Price for overall consumption of electrical power in 1 year [HRK]	**533.896,68**

b)

6. Discussion on obtained results

As seen in Tables 9 and 10 a and b, the solution with constant volume flow through the entire evaporator part of the plant is not cost-effective considering the variety of consumers and their join in different modes during the year and considering the price of electrical energy.
A solution should be sought in a cooling plant with variable volume flow. However, this depends on the number of consumer circles. We already had two major separate consumer circles in this context, where the solution with circulating pumps with variable volume flow in the primary circle was found to be appropriate. Compared to the constant volume flow solution, up to 43% of the electrical energy costs may be saved.
As regards other cases not presented in this case study, the solution would also probably be a combination of a primary circle with constant volume flow and a secondary circle with variable volume flows. Of course, this depends on the architecture of the cooling plant.
As mentioned above, no evaluation analysis was performed for the condenser part of the cooling plant as its electrical energy consumption is insignificant compared to the amount of electricity used by the evaporator part of the plant. In addition, the architecture of this part of the system is the same in all iteration steps (it was not changed), so it was not necessary to perform an evaluation analysis on this side of the system. In case we had several different architectures for the condenser part subsystem in different iteration steps, it would be necessary to perform an evaluation analysis on this side as well (e.g., primary and secondary circles in the condenser part separated by a plate exchanger, where a primary and a secondary circle exist).
The design of the cooling plant, such as the one selected in this case study that is more energy efficient and includes variable primary flow [TRANE 2009], [Hanson et al. 2009] (VPF – system architecture 2), also requires more complex automated control of its operation compared to the system solution with variable secondary flow (system architecture 1) or systems using constant volume flow. Of course, the energy efficiency and reliability of the cooling plant also depend on the software controlling such a complex technical system (eg. example of TRANE's integrated solution Chiller Plant Control (CPC) ® managing the cooling plant's system in case its water chillers operate on a parallel basis) [TRANE 2010a]. However, the design of the automated control system was not addressed in this paper.

7. Conclusion and future research

The paper presents research that was used to develop a methodology for the development of complex technical system (cooling plants) architectures based on an evaluation for the purpose of selecting a system that is more energy efficient, i.e. a system using less electrical energy. This methodology was primarily developed to assist all designers (professionals) who are engaged in the development of cooling plants to allow them to obtain a satisfactory solution as quickly and efficiently as possible. Methodology presented here is based on author's expierence and describe a design of cooling plant how it is really doing in industry sector. This implies developing a system architecture referring to the selection of such proposed system that will use the least electrical energy (which would be an acceptable result) with lowest price and with smallest deviation in system performance.

The verification of the system is presented in this paper by a case study of a complex technical system, a cooling plant with water based chilers for indoor installation in the pharmaceutical industry. The case study shows that the methodology presented may be used to obtain an acceptable solution very quickly through a couple of iteration steps. The case study includes an evaluation analysis of electrical energy consumption on the evaporator side of the plant (consumers), where the individual and aggregate consumption of electrical energy and its cost were calculated on the basis of the circulating pumps' operating time under specific partial system loads. Of course, the automated control of the plant also plays an important role in achieving an energy efficient system. However, it was not addressed in this paper.

This research could be extended to or in future directed toward the development of a computer algorithm which would itself be able to propose a solution for a system architecture of cooling plant based on the required input cooling load and other parameters, the consumer types and number and the time of their operation during the year being the most influential ones among them. This refers to proposing the type and number of equipment items (chillers, cooling towers, circulating pumps etc.). Such algorithm would also be able to record the systems selected and use the system architecture obtained in a similar system (by modification or reevaluation).

References

Albers, A., Martin, P., Geiger, S., "Analyzing the Project-SpecificRelevance Of Energy Efficiency as a Design Objective", Proceedings of DESIGN 2014, Vol.1, Dubrovnik, Croatia, 2014, pp. 91-100.

Ardissono, L., Felfernig, A., Friedrich, G., Goy, A., Jannach, D., Meyer, M., Petrone, G., Schäffer, R., Schütz, W., Zanker, M., "Customizing the Interaction with the User in On-Line Configuration Systems", Proceedings of ECAI 2002 Workshop on Configuration, 2002, pp. 119-124.

Bonvoisin, F., Mathieux, L., Domingo L., Brissaud D., "Design for Energy Efficiency: Proposition of a guideline based tool", Proceedings of DESIGN 2010, Dubrovnik, 2010, pp. 629-638.

Brezet, H., van Hemel, C., "EcoDesign. A promising approach to sustainable production and consumption", 1st edition, United Nations Publications, Paris, France, 1997.

Claesson, A., Johannesson, H., Gedell, S., "Platform product development: product model – a system structure composed of configurable components", Proeedings of 2001 ASME Design Engineering Technical Conferences, Pittsburgh, USA, 2001.

Donjerković, P., "Fundamentals and Control of Heating, Ventilattion and Air-conditioning systems – part I and II", (in Croatian), Alfa, Zagreb, 1996.

Energy Design Resources: "Chiller Plant Efficiency –Design Brief", Energy Design Resources, USA, 2010.

Fujita, K., Akagi, S., Yoneda, T., Ishikawa, M., "Simultaneous optimization of product family sharing system structure and configuration", Proceedings of 1998 ASME Design Engineering Technical Conferences, Atlanta, USA, 1998.

GRUNDFOS, "TP Direct-coupled in-line single stage circulator pumps", GRUNDFOS product guide, Denmark, 2012.

Hanson, S., Schwedler, M., Bakkum, B., "Chiller System Design and Control", TRANE Applications Engineering Manual, USA, 2009.

Heiskala, M., Anderson, A., Huhtinen, V., Tiihonen, J., Martio, A., "A Tool for Comparing Configurable Products", Workshop on Configuration in the 18th International Joint Conference on Artificial Intelligence, American Association for Artificial Intelligence, Acapulco, Mexico, 2003, pp. 64-69.

Hubka, V., Eder, W. E., "Engineering Design: General Procedural Model of Engineering Design", Springer – Verlag Berlin Heidelberg, Germany, 1992.
Hubka, V., Eder, W. E., "Theory of Technical Systems – A Total Concept Theory for Engineering Design", Springer – Verlag Berlin Heidelberg, Germany, 1988.
Kortler, S., Kohn, A., Lindemann, U., "Validation of Product Properties Considering a High Variety of Complex Products", Proceedings of DESIGN 2012, Dubrovnik, 2012, pp. 1731-1740.
Lechner, A., Klingebiel, K., Wagenitz, A., "Evaluation of Product Variant-driven Complexity Costs and Performance Impacts in the Automotive Logistics with Variety-driven Activity-based Costing", Proceedings of the International MultiConference of Engineers and Computer Scientists, IMECS 2011, Hong Kong, China, 2011.
Lindemann, U., Maurer, M., Braun, T., "Structural Complexity Management – An Approach for the Field of Product Design", Springer Verlag Berlin Heidelberg, Germany, 2009.
Martin, M., Ishii, K., "Design for variety: a methodology for understanding the costs of product proliferation", Proceedings of 1996 ASME Design Engineering Technical Conference, Irvine, USA, 1996.
Martin, M., Ishii, K., "Design for variety: development of complexity indices and design charts", Proceedings of 1997 ASME Design Engineering Technical Conference, Sacramento, USA, 1997.
Menon, E. S., Menon, P. S., "Working Guide to Pumps and Pumping Stations - Calculations and Simulations", Elsevier, USA, 2010.
Nayak, R. U., Chen, W., Simpson, T. W., "A Variation - based Methodology for Product Family Design", Proceedings of Proceedings of DETC'00 ASME 2000 Design Engineering Technical Conferences, USA, 2000.
Niemann, J., Tichkiewitch, S., Westkämpfer, E. (Eds.), "Design of Sustainable Product Life Cycles", Springer Berlin Heidelberg, 2009.
Otto, K., Wood, K., "Product Design: Techniques in Reverse Engineering and New Product Development", 1st edition, Prentice Hall, USA, 2000.
Pargamin, B., "Vehicle Sales Configuration: the Cluster Tree Approach", ECAI 2002 Workshop on Configuration, 2002, pp. 35-40.
Pedersen, K., Messer, M., Allen, J. K., Mistree, F., "Hierarchical product platform design: a domain-independent approach", Ships and Offshore Structures, Vol.8, No.3-4, 2013, p. 367.
Rath, K., Birkhofer, H., Bohn, A., "Which Guideline is Most Relevant? Introduction of a Pragmatic Design for Energy Efficiency Tool", Proceedings of ICED 2011, Kopenhagen, Denmark, 2011.
Rath, K., Röder, B., Birkhofer, H., Bohn, A., "Standardized Requirement Acquisition Through Clustering: a Tool for Energy-efficient Products", Proceedings of DESIGN 2012, Vol.1, Dubrovnik, Croatia, 2012, pp. 1081-1090.
Recknagel, H., Sprenger, E., Schramek, E.-R., Čeperković, Z., "Heaating and Air-conditioning 2012", Interklima, Vrnjačka Banja, Serbia, 2012.
Rissanen, N. E., Malmqvist, J., Pulkkinen, A. J., "Evaluating the Structural Complexity of a Product Family", Proceedings of DESIGN 2012, Dubrovnik, 2012, pp. 1597-1604.
Saheb, Y., Becirspahic, S., Simon, J., "Effect of the Certification of Chillers Energy Efficiency", Proceedings of IEECB 2006, Frankfurt, Germany, 2006, pp. 4-9.
Simon, H. A., "The New Science of Management Decision", Harper and Row, New York, USA, 1960.
Stolze, M., "Comparative Study of Analytical Product Selection Support Mechanisms", Proceedings INTERACT 99, Edinburgh, Scotland, 1999, pp. 45-53.
TRANE, "Centrifugal Water Chillers", TRANE Applications Engineering Manual, USA, 1999b.
TRANE, "Chilled Water Systems", TRANE Applications Engineering Manual, USA, 2001.
TRANE, "Chiller Plant Control", TRANE Applications Engineering Manual, USA, 2000a.
TRANE, "Helical Rotary Chillers", TRANE Applications Engineering Manual, USA, 1999a.
TRANE, "Refrigeration Compressors", TRANE Applications Engineering Manual, USA, 2000b.
Tseng, M. M., Jiao, J., "Design for mass customization by developing product family architecture", Proceedings of 1998 ASME Design Engineering Technical Conference, Atlanta, USA, 1998.
Wang, F., Linb, H., Tub, W., Wanga, Y., Huanga, Y., "Energy Modeling and Chillers Sizing of HVAC System for a Hotel Building", Procedia Engineering, Vol.121, 2015, pp. 1812-1818.

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