2012

A Software Application for the Selection of Temperature Measuring Sensors Using the Analytic Hierarchy Process (AHP)

Tarek Al-Hawari

Shadi Mohammad AL-B'ool
Binghamton University--SUNY, salbool1@binghamton.edu

Amer Momani

Recommended Citation
Al–Hawari, T., Al–Bo'ol, S., & Momani, A. M. (2012). A software application for the selection of temperature measuring sensors using the analytic hierarchy process. International Journal of Computer Applications in Technology, 44(3), 198-209. doi: http://dx.doi.org/10.1504/IJCAT.2012.049083

A Software Application for the Selection of Temperature Measuring Sensors Using the Analytic Hierarchy Process (AHP)

Tarek AlHawari [a,1], Shadi AlBo'ol [b,*]

[a,1]Assistant Professor, Department of Industrial Engineering, Faculty of Engineering, Jordan University of Science and Technology, Irbid, Jordan
[b,*]Department of Industrial Engineering, Faculty of Engineering, Jordan University of Science and Technology, Irbid, Jordan

Abstract

For an accurate and efficient industrial process, many physical and chemical process variables are directly or indirectly measured, monitored and controlled through the use of different types and configurations of process sensors and transducers, of which temperature sensors are of great importance and are at the heart of almost every application of process industries. This study presents a computer program that applies analytic hierarchy process (AHP) method to objectively select the best temperature sensors for various applications from multiple nominated alternatives. The underlying decision method based on AHP methodology, ranks temperature sensors with different features with a score resulting from the synthesis of relative preferences of each alternative to the others at different levels considering independent evaluation criteria. At each level, relative preferences of each candidate alternative with respect to the upper immediate level are calculated from pair-wise comparisons among the candidate alternative sensors based on the specifications of sensors with respect to a selected application. These pair-wise relative comparison weights are embedded in the computer software and are retrieved whenever the user specifies the application, the restrictions, and the available alternative sensors that meet these restrictions. AHP method proves to provide a quantitative and rational alternative performance evaluation method, it permits simpler, easier and more organized decision making process than subjective opinions that are subject to erroneous judgments. In this study, the application of AHP method in selecting the best temperature sensor for a particular application is embedded via the use of a computer program built using C# programming language to help perform the selection process in an easy graphical user interface GUI, ready-to-use, and computerized way and thus provides aid to those working in industry and in need of such a software tool.

1. Introduction

The ultimate goal of any industrial company is to gain profit. In order to do so, it is vital for the company to maintain their industrial operations and processes at the most efficient and accurate level of process operation which calls for the use and application of multitude of process measurement and control systems. In this sense, a process consists of various sequential manufacturing operations that start with raw materials (such as chemicals or feed stock) and converts it into a useful product that can be sold with profit gaining certain amount of added value. And because we live in a highly competitive industrial environment today that imposes stringent requirements on product quality, it is ultimately the need for a company to survive in the market by providing an adequate and profitable return on stockholder investment that provides the motive behind purchasing measurement and control equipment. Process sensors are the devices that measure process variables, the resulting data from the measurement is used to control and monitor the process, and to take correction actions if needed [1]. In addition, process measurement enables better understanding of the process, which is a preliminary step for process improvement and development. The connection between profit and process measurement is illustrated in Figure 1.

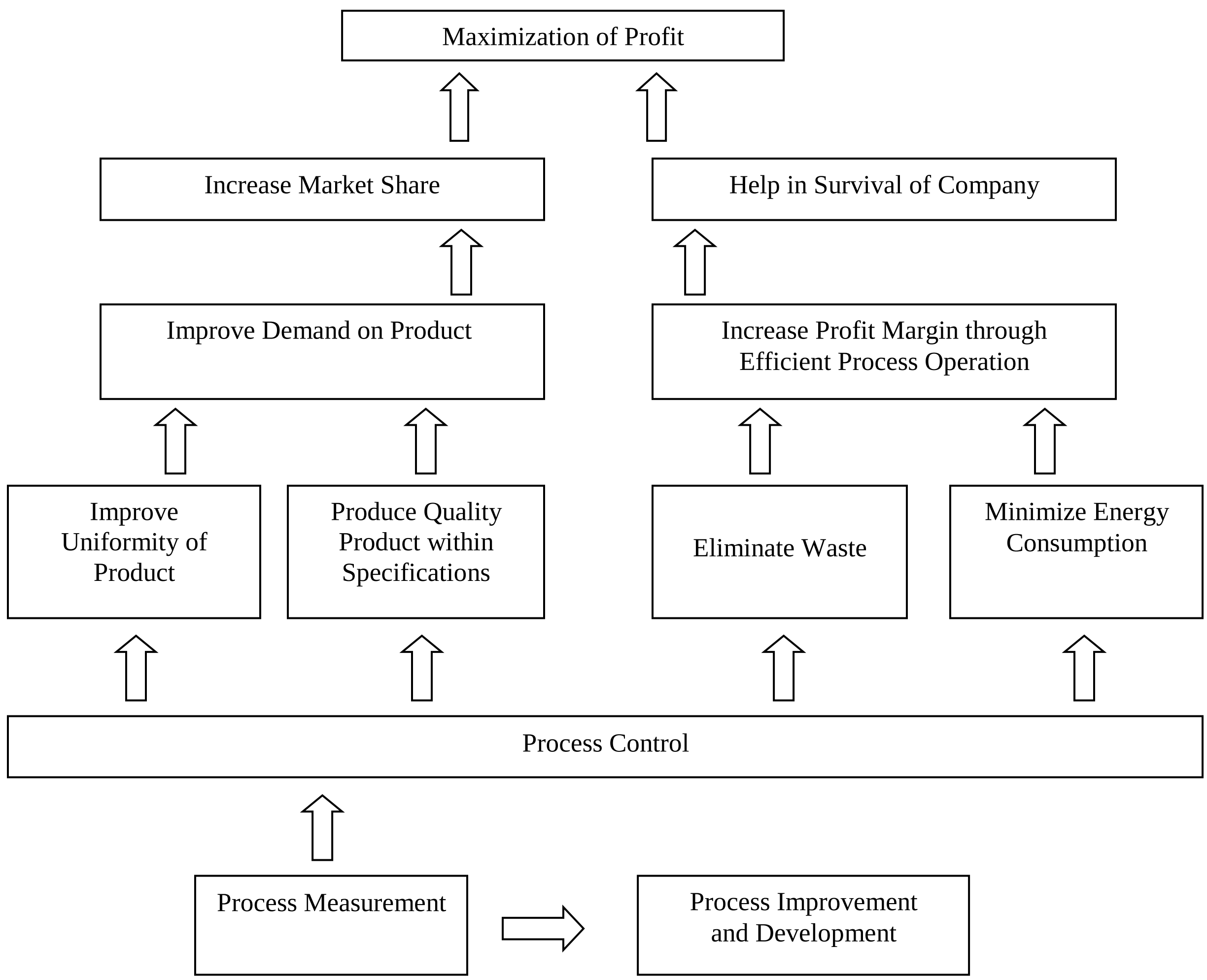


Figure1: Crucial Importance of Process Measurement for Plant Profitability

Instruments for the measurement of temperature are available in a wide range of configurations. One is the very common liquid-in-glass thermometer. A range of dial thermometers that provide a local reading are available in process industry. Remote reading instruments are also available where the measuring system operates the dial directly through the length of metal capillary tubing with distance between the sensing ‘bulb’ and the dial, or readout, the distance of these instruments is limited to about thirty meters. Where the temperature readout is required at longer distances from the location of the sensing element there are two main options; either an electrical measuring technique such as a thermocouple or resistance thermometer RTD can be used or where the distances between the plant measurement locations and the control room are very long it is usually better to use temperature transmitters. Temperature transmitters use the same types of temperature probes as other temperature measuring instruments. The transmitting mechanism is normally attached directly to the probe. It may also have a local readout facility as well as its transmitting function which is to convert the measurement effect into a pneumatic or electrical signal suitable for transmission over long distances and reachable to a display digital screen that may be located far in a control room [2].

2-Literature Review

Previous literature indicates the massive use of AHP methodology as a multi-criteria decision making tool in selecting from among nominated alternatives in many industrial fields. However the literature survey has not revealed any research conducted specifically on the selection of temperature sensors using AHP method, and here comes to the fore the importance of this study. Omkarprasad S. Vaidya and Sushil Kumar [3] conducted a research that overviewed different applications of Analytic Hierarchy Process method. In their paper, they presented a literature review of various applications of Analytic Hierarchy Process (AHP), they referred to a total of 150 application papers, of which 27 were critically analyzed. In their work, they analyzed the applications papers according to three main groups: (a) applications based on a theme, (b) specific applications, and (c) applications combined with some other methodology, with all application papers in specific group given distribution in the form of a pie-chart. Some theme-specific applications which were mentioned in the paper were using AHP in: selection, evaluation, benefit-cost analysis, resource allocation, decision making, forecasting, medicine, and QFD. Some application area-specific papers were in: social, political, manufacturing, engineering, education, industry, government, and others. And finally, distribution of reviewed papers over the years was investigated in the form of a pie-chart. Mustafa Yurdakul [4] has applied AHP method as a strategic decision-making tool to justify machine tool, namely machining centers, selection. He tested AHP approach in his research based on three-machining centre case study for Dizayn Machinery Manufacturing and Engineering Inc., located in Ankara, Turkey, in which case the company opted to purchase new machine tools in order to reduce lead times without compromising quality and cost of its products. Analytic Hierarch Process (AHP) method was used to combine different types of evaluation criteria in a multi-level decision structure to obtain a single score for each alternative machine tool to rank the alternatives. Analytic Network Process (ANP) method was used in the same paper to account for calculation of real weight of criteria due to interdependencies and interrelationships that really do exist among the evaluation criteria. Yurdakul stated that the company management found the application and results satisfactory and implementable in their machine tool selection decisions. Pi-Fang, Cheng-Ru, and Ya-Ting [5] presented an AHP method in objectively selecting medical waste disposal firms in Taiwan based on the results of interviews with experts in the field. In their study, an appropriate weight criterion based on AHP was derived to assess the effectiveness of medical waste disposal firms. The proposed AHP-based method in the paper offered a more efficient and precise means of selecting medical waste firms than subjective assessment methods did, thus reducing the potential risks for hospitals. Che-Wei et al [6] studied and developed a manufacturing quality yield model for forecasting 12 in. silicon wafer slicing machine based on AHP framework. In their work, Exponentially weighted Moving Average EWMA control chart was presented to demonstrate and verify the feasibility and effectiveness of the proposed AHP-based algorithm, and selective analysis was performed to test the stability of the priority ranking. Okada, H. et al [7] applied AHP to irrigation project improvement.

Despite the fact that literature survey reveals wide array of papers applied in AHP for different applications, the survey does not reveal its use in evaluating temperature sensors alternatives, rather, research on temperature sensors was primarily concerned about proposing new temperature sensors fabrications that satisfy certain special demands and requirements of the proposed sensor. Vavra, I. et al [8] proposed the use of Fe/Cr magnetoresisitive sensors at temperatures below 2 K in the milliKelvin temperature range. Hoa, C.H. et al [9] studied electrical resistance drift of molybdenum disilicide ($MoSi_2$) thin film temperature sensors to study their thermoresistance, i.e. resistance vs. temperature (R-T) characteristics. Bianchi, R. A. et al [10] discussed the properties, characteristics, applications and sensing principles of most of present-day integrated smart temperature sensors. A CMOS process-compatible temperature sensor developed for low-cost high-volume integrated Microsystems for a wide range of fields (such as automotive, space, oil prospecting, and biomedical applications) was also described. Han, Y., & Kim, S. J. [11] developed a diode temperature sensor array (DTSA) for measuring the temperature distribution on a small surface with high resolution. The DTSA consisted of an array of 32x32 diodes (1024) for temperature detection in an 8mmx8mm surface area and was fabricated using the very large scale integration (VLSI) technique.

This study presents a computer program built using C# programming language to perform the selection process of the best temperature sensor for a particular application from among available alternative sensors that meet the restrictions set by the program and chosen by the user, this is done by applying imbedded AHP method in a ready-to-use and in an easy graphical-user-interface computerized way. The proposed computer program is versatile and applicable to multitude of temperature sensors selection situations, but it should be noticed that as means of exemplification of the proposed program, the work in this paper relates only to a single case study in which a single application is considered which is automotives industry and in which three temperature sensors are being assessed and compared, these are: thermocouple, thermistor and RTD thermometer. Nonetheless, the computer program is more robust and applicable to verily a wider range of temperature sensors selection situations with different application and different array of candidate sensors.

3. General Description of the computer software

In this study, the computer program that is used for the selection process of the best sensor from among different alternative sensors was built using Microsoft Visual Studio.NET programming language. Starting from a C# Windows application template, a base -code project was created in which a two-page form was designed to show sensor selection based on AHP principles.

The first page in the form is used to select the application from three predefined applications: HVAC, Automotives, and Chemical Reactions. In the first page also lie restrictions applicable to the mentioned applications that the user should specify and that are: Temperature Range, Accuracy, and Response time. Upon user’s selection of the application required and restrictions pertaining to that application in the first page, the second page tab can be pressed to list the available alternative candidate sensors which can be used in the selected application and that the user can further choose from. These available alternative sensors would appear in activated checkboxes, while those sensors that do not conform to the restrictions set and chosen by the user in the first page will automatically be shown by the system in an inactivated- checkbox mode in the second page, and thus the user can not choose from.

Upon practical application, the user selects the application in page one and depending on the restrictions selected some sensors will be enabled while the others will be disabled in page two. Upon selection button press in the second page, the results of the calculations that are automatically based on AHP method will be displayed and the results will be sorted starting from the best sensor at the top and ending with the worst choice for the application at the bottom of the list. Relevant calculations of weights of sub-criteria, weights of criteria, consistency ratio, consistency index and final scores of the alternative sensors are all shown on the console provided inside the second page.

When the application is to be shown on the screen, the form will be loaded by the system (Windows Operating System) and the main form of the application will initialize the restrictions dropdown lists with their values and will select the default application which is Automotives in this program.

4. Method Application and Results Using the Computer Software

In order to select the best temperature sensor among the three sensors, six distinct steps are performed in the application of the imbedded AHP method inside the software. First, start up the computer program. Second, specify the evaluative criteria and sub-criteria pertinent to sensor industry and upon which the three candidate sensors will be pair-wise compared. These criteria and sub-criteria are fixed in the software. Second, establish the decision hierarchy for temperature sensors selection problem. This hierarchy is made up of four levels, each level consists of multi components that belong to an immediate upper parent component in the immediate upper level. This hierarchy is also imbedded inside the software, and is not shown to the user. Next, determine the weights (contributions) of each component of the hierarchies by means of pair-wise comparisons performed among the three alternative sensors, these weights are built-in values imbedded inside the software, and are being aggregated to obtain the weight of the components in the immediate upper level. Fourth, the software calculates the weights for the whole components in the hierarchal structure, synthesizes the contribution of the components for the whole hierarchy and for all levels up to display the overall ranking scores for the three alternatives on the software console. Finally, the software performs the consistency test in terms of consistency index and consistency ratio which can be regarded as a measure of consistency in decision maker's comparisons and displays these indices on the same console.

4.1. Starting the computer program

Following the path: start>All Programs>Microsoft Visual Studio 2005> Open: Project…> My Computer>Local Disk (D:) > AHP folder>AHPCaseStudy1GUI> AHPCaseStudy1GUI.sln. A window of the application will open as shown in Figure 2.

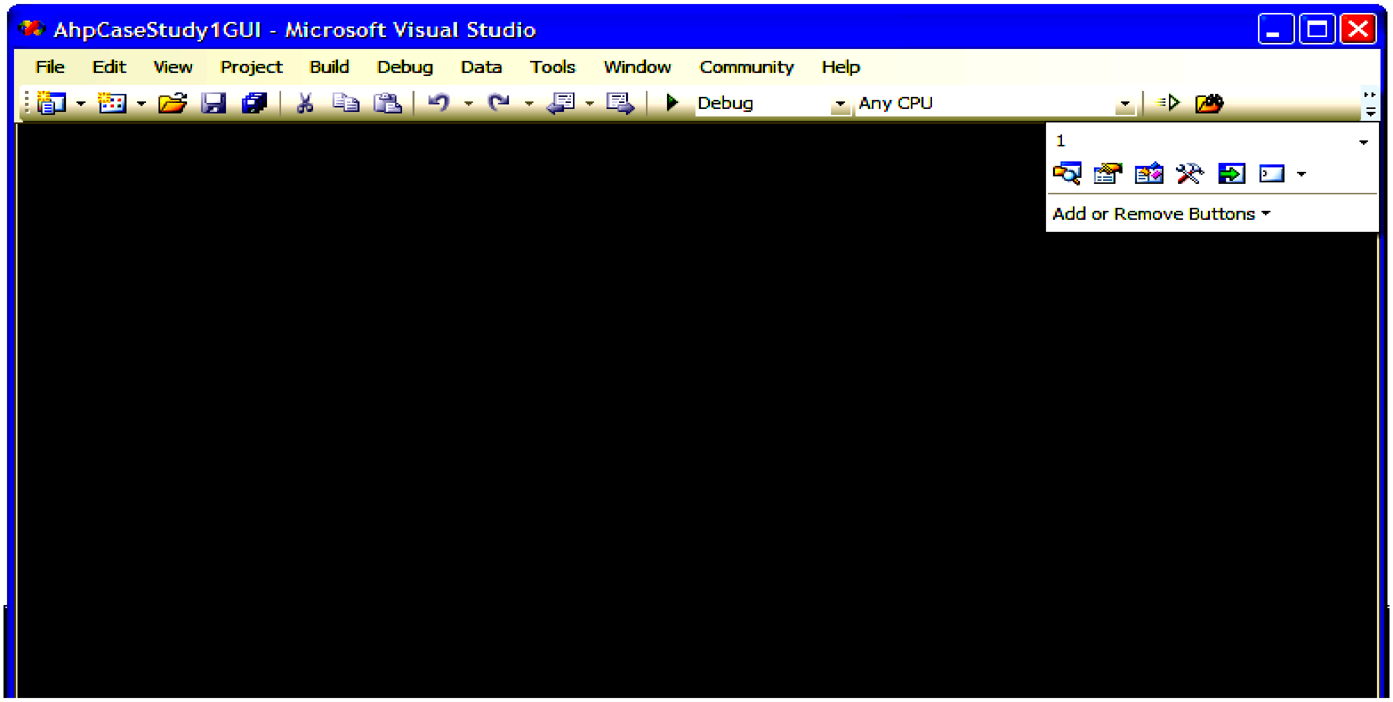


Figure 2 The main window of the application

The Solution Explorer tab may not be visible. If so, visualize it by pressing the Solution Explorer icon at the top right of the main window as shown in Figure 3.

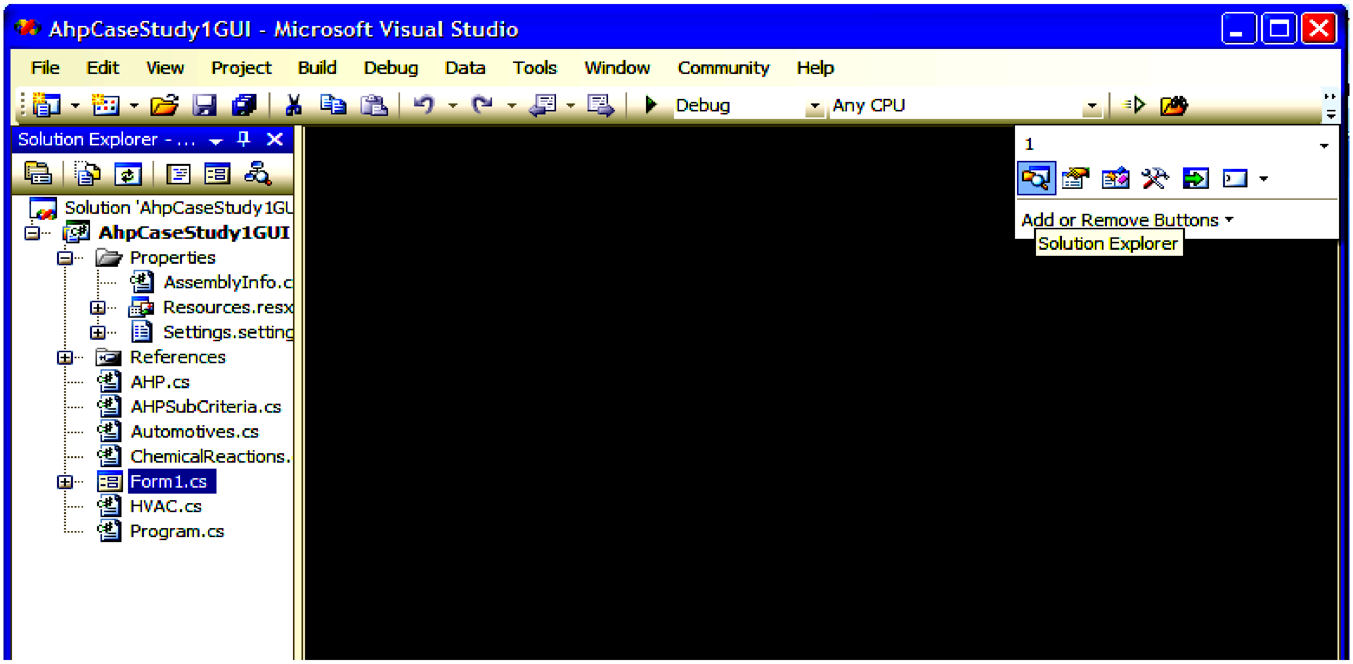


Figure 3 visualizing Solution Explorer tab

For visualizing the GUI main window from which the selection process of the best sensor will be launched, the user will first need to double click the C# file named Form1.cs in the Solution Explorer tab at the far left side of the application window. See Figure 4.

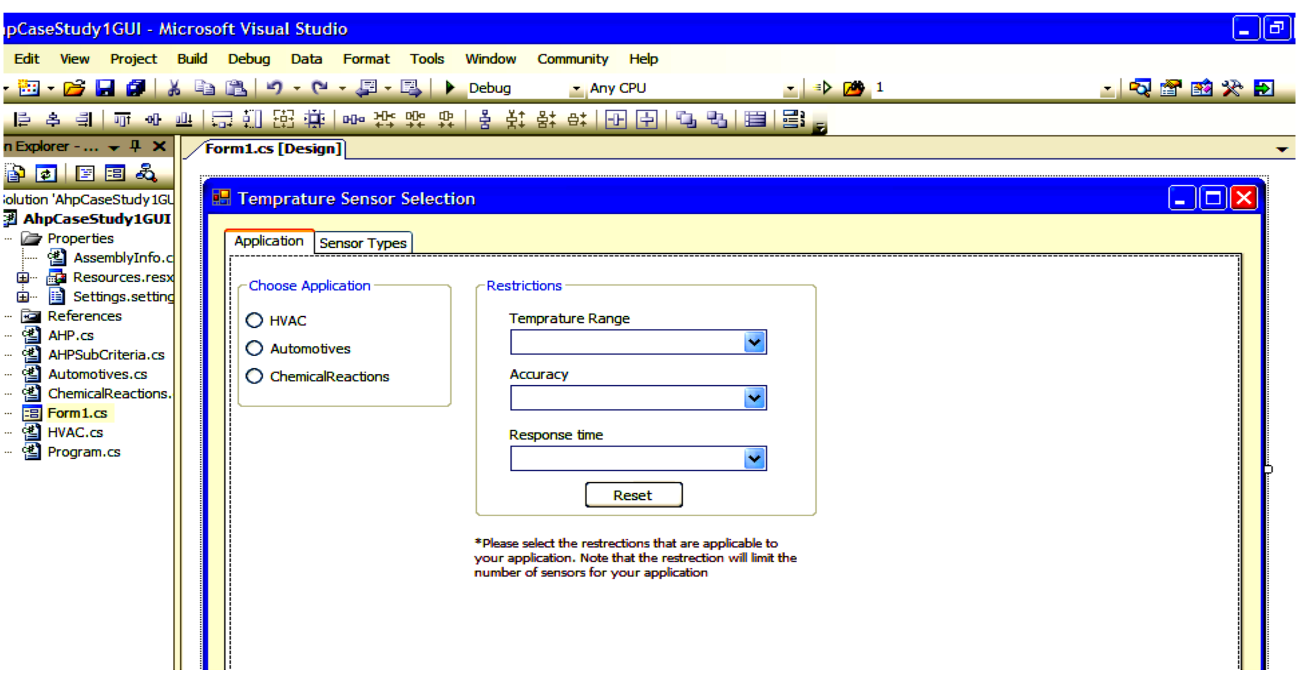
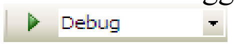


Figure 4 The two-tab page GUI main window

In the GUI main window appears the two-tab page. From which page the user can choose the application under concern as well as the restrictions pertaining to that application in terms of Temperature Range, Accuracy, and Response Time, this can be done from the first tab. Upon completion of the first tab, he can proceed to the next tab where available candidate alternative sensors that meet the restrictions set in the first page for the application under concern are listed in an activated checkbox mode, and those alternative sensors that do not conform to restrictions are disabled and shown in an inactivated mode. It is worth noting; however, that the user can not use this window as is since it is a design form window. He can use the window and choose from the two tabs upon user's debugging of the design form file. This is accomplished when the user presses the Debug button 

which will enable the implementable GUI window. See Figure 5.

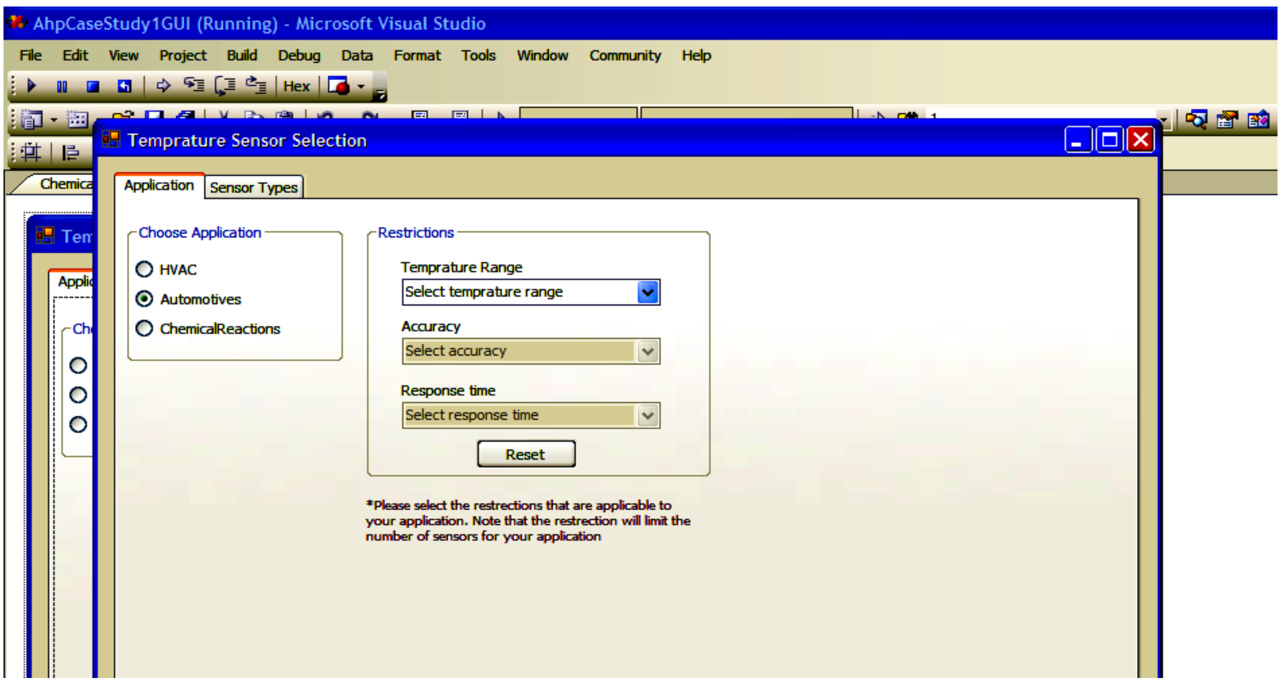


Figure 5 Implementable GUI two-tab page window used by the user for the selection process. Note the default application Automotives. The first Tab shows the applications and restrictions pertaining to these applications.

Figure 6 shows the components of the second tab.

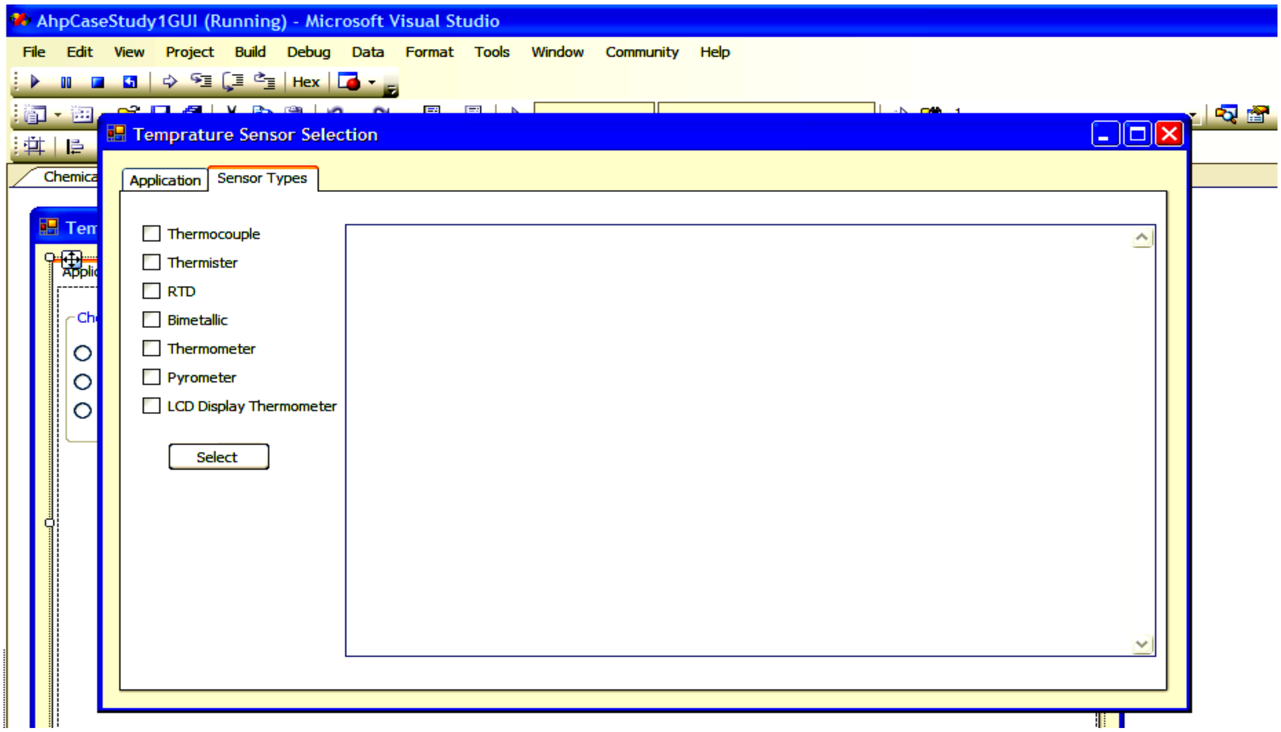


Figure 6 Alternative sensors found in second tab in the application main window

4.2. The Evaluative Criteria and Sub-criteria

Upon literature survey in the field of sensors and sensors selection, four broad criteria were settled on, within each criterion lie multiple sub-criteria. These parent criteria and sub-criteria form the basis for the comparison between alternative sensors. Table 1 shows these criteria and sub-criteria. These criteria and sub-criteria are incorporated inside the software.

Table 1
Criteria and sub-criteria factors used as basis for comparison between alternative sensors

Criteria	Sub-Criteria
Static Criteria (C1)	Maximum Operating Temperature (CS1) Minimum Operating Temperature (CS2) Temperature Curve (CS3) Maximum Sensitivity Region (CS4) Self-Heating Issues (CS5) Long Term Stability and Accuracy (CS6) Typical Temperature Coefficient (CS7) Extension Wires (CS8) Long Wire runs from Sensor (CS9) Measurement Parameter (CS10) Temperature Measurement (CS11)
Dynamic Characteristics (C2)	Stimulation Electronics required (CS12) Typical Output Levels per Degree Celsius (CS13) Typical Fast Thermal Time Constant (CS14)

Environmental Parameters (C3)	Typical Small Size (CS15) Noise Immunity (CS16) Fragility-Durability Characteristics (CS17) High Thermal Gradient Environment (CS18) Corrosion Resistance (CS19)
Other Criteria (or Simply Others) (C4)	Point or Area Measurement (CS20) Manufacturing Variances (CS21) NIST Standards (CS22) Cost (CS23)

4.3. The hierarchal Structure

The best temperature sensor can then be selected and evaluated by the software based on four evaluation criteria, twenty –three evaluation sub-criteria and, finally, the alternatives. Figure 7 shows the hierarchal structure for the temperature sensor selection problem. The software is programmed to automatically perform calculations based on the hierarchal structure shown in Figure 7.

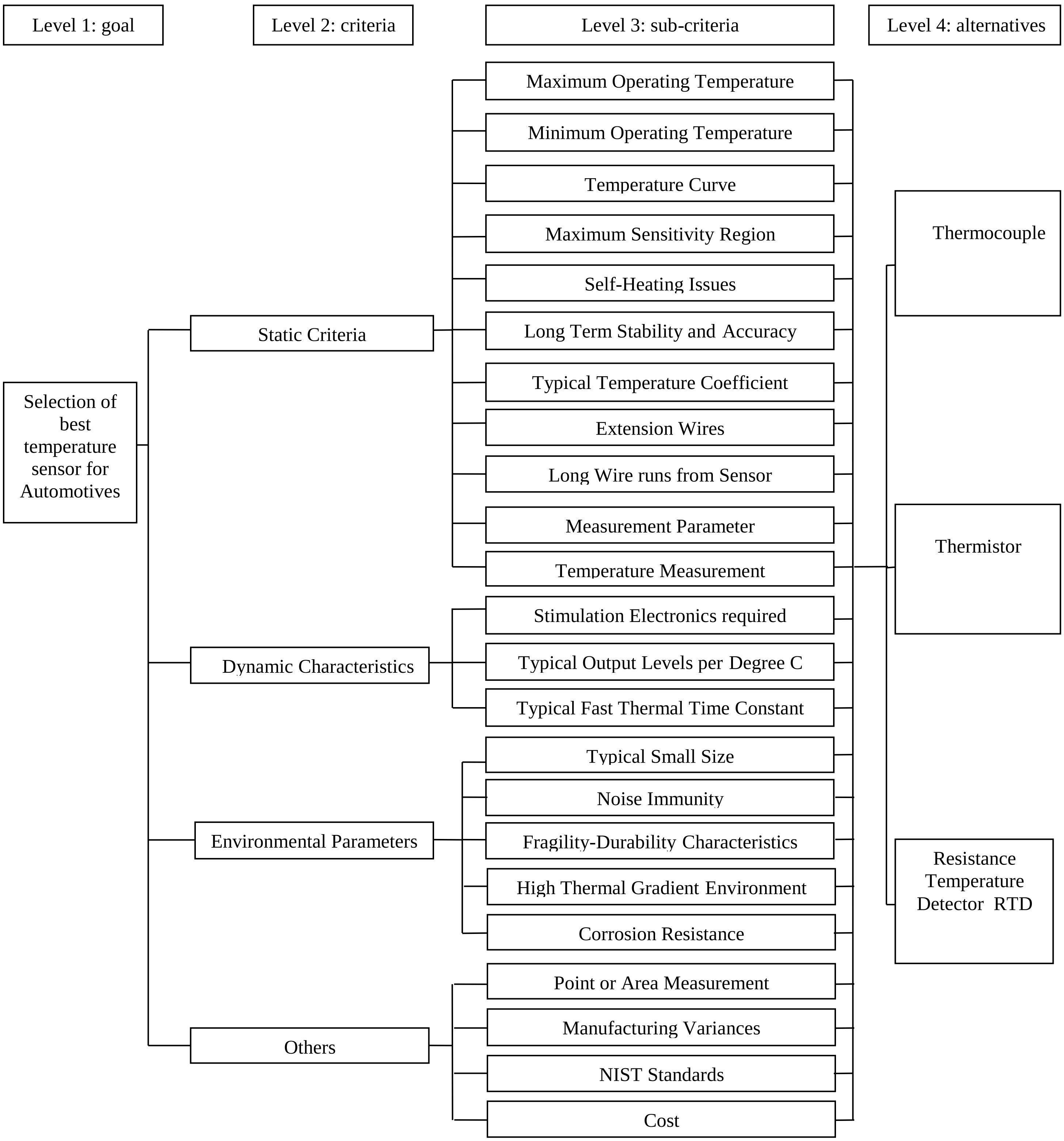


Figure 7: Hierarchical structure to select the best sensor in Automotives industry

4.4. Calculation of Component Weights

In this step, relative comparison weights of each available candidate alternative sensor against other available alternatives are retrieved by the system from built-in values, and weights of all components in the hierarchal structure are determined and calculated automatically by the software. These components are assumed to be independent so that AHP method can be used. The system aggregates the weights of components in lower levels to obtain weights of upper immediate parent components in the immediate upper levels. Specifically speaking, this step consists of the following three sub-steps:

4.4.1. The software calculates the score of each sensor relative to each other with respect to each sub-criterion

In this step, a question of the type: how well the first alternative scores relative to the other two with respect to each sub-criterion, is asked. In doing so, 23 relative pair-wise comparison matrices of the dimensions 3x3 whose rows and columns represent the relative preference of one alternative sensor to the other were constructed and embedded inside the system. The relative importance of one alternative over the other with respect to the same parent component in a decision hierarchy can be determined using Saaty's scale (Table 2). According to Saaty, the relative weight of component *i* compared to component *j* with respect to the same parent component is obtained from a 9-point scale and assigned to the (*i* , *j*)th position of the pair-wise comparison matrix.

Table 2
The pair-wise comparison scale (Saaty, 1990)

Intensity of importance	Definition
1	Equal importance both element
3	Weak importance one element over another
5	Essential or strong importance one element over another
7	Demonstrated importance one element over another
9	Absolute importance one element over another
2, 4, 6, 8	Intermediate values between two adjacent judgments

Let $A1, A2, \dots, An$, be the set of stimuli. The quantified judgments on pairs of stimuli Ai ,Aj, are represented by:

$$A = [aij], \qquad i, j = 1, 2, \dots, n \qquad (1)$$

Saaty's scale is used to transform verbal judgments of relative preference of one alternative to the other into numerical quantities representing the values of aij. The entries aij are governed by the following rules:

$$aij > 0, \qquad aji = \frac{1}{aij}, \qquad aij = 1 \text{ for all } i. \qquad (2)$$

Thus, the reciprocal of the assigned value is automatically assigned to the (*j*, *i*)th position. After the pair-wise comparison matrices have been established, the weights of the different components, the three sensors here, with respect to each sub-criterion can be calculated by solving for the eigenvector of the pair-wise comparison matrices that relate to the same sub-criteria respectively. After the pair-wise comparison matrices A_k.s have been constructed, the system recovers the numerical weights ($\boldsymbol{W1}$,$\boldsymbol{W2}$, …, $\boldsymbol{Wn}$) of the alternatives. Consider the following equation:

$$A = \begin{pmatrix} a11 & a12 & \dots & a1n \\ a21 & a22 & \dots & a2n \\ . & \dots & . & . \\ . & \dots & . & . \\ an1 & an2 & \dots & ann \end{pmatrix} = \begin{pmatrix} W1/W1 & W1/W2 & \dots & W1/Wn \\ W2/W1 & W2/W2 & \dots & W2/Wn \\ . & . & \dots & . \\ . & . & \dots & . \\ Wn/W1 & Wn/W2 & \dots & Wn/Wn \end{pmatrix}$$

, for a perfectly consistent decision maker. (3)

$$A = \begin{pmatrix} a11 & a12 & \dots & a1n \\ a21 & a22 & \dots & a2n \\ . & \dots & . & . \\ . & \dots & . & . \\ an1 & an2 & \dots & ann \end{pmatrix} \approx \begin{pmatrix} W1/W1 & W1/W2 & \dots & W1/Wn \\ W2/W1 & W2/W2 & \dots & W2/Wn \\ . & . & \dots & . \\ . & . & \dots & . \\ Wn/W1 & Wn/W2 & \dots & Wn/Wn \end{pmatrix}$$

, for not perfectly consistent decision maker. (4)

Let us multiply both sides of the equation (3) with the weights vector $\boldsymbol{W}$= ($\boldsymbol{W1}$,$\boldsymbol{W2}$, …, $\boldsymbol{Wn}$), then we have:

$$\boldsymbol{AW}^{T} = \Delta \boldsymbol{W}^{T}. \quad (5)$$

This is a system of homogenous linear equations, where Δ is an unknown number and $\boldsymbol{W}^{T}$ is an unknown n-dimensional column vector [12], for any number Δ, (5) always has the trivial solution $\boldsymbol{W}$= (0, 0, ..., 0). It can be shown that if A is the pair-wise comparison matrix of a perfectly consistent decision maker, i.e. equation (3) applies, and we do not allow Δ = 0, then the only nontrivial solution to (5) is Δ = *n* and $\boldsymbol{W}$= ($\boldsymbol{W1}$,$\boldsymbol{W2}$, …, $\boldsymbol{Wn}$). However, if the decision maker is not perfectly consistent, i.e. equation (4) applies in this case, then let Δ_{max} be the largest number for which (5) has a nontrivial solution (call it $\boldsymbol{W}_{max}$) . Saaty verified that if the decision maker's comparisons do not deviate very much from perfect consistency, then Δ_{max} is close to *n* and $\boldsymbol{W}_{max}$ is close to $\boldsymbol{W}$. Saaty also proposed measuring the decision maker's consistency by looking how close Δ_{max} is to *n*.
A simple method [12] is used and imbedded in the system to automatically approximate Δ_{max} and $\boldsymbol{W}_{max}$ and the index of consistency which comprises the following two steps:

1-The system finds the normalized matrix A_{norm}. This can be done by dividing each entry for each of A's columns by the sum of all entries in the same column.
2- To find an approximation to $\boldsymbol{W}_{max}$ which will be used as an estimate of $\boldsymbol{W}$, the system estimates $\boldsymbol{W}_i$ as the average of the entries in row *i* of A_{norm}.

For the Automotives application, and more specifically, the catalytic converter application as part of Automotives application, the first tab in the software was chosen Automotives application, restrictions pertaining to catalytic converter were temperature range -100 to 1000 °C, Accuracy 0.1°C, and response time 1 seconds. Figure 8 shows the first page selection for the Automotives application.

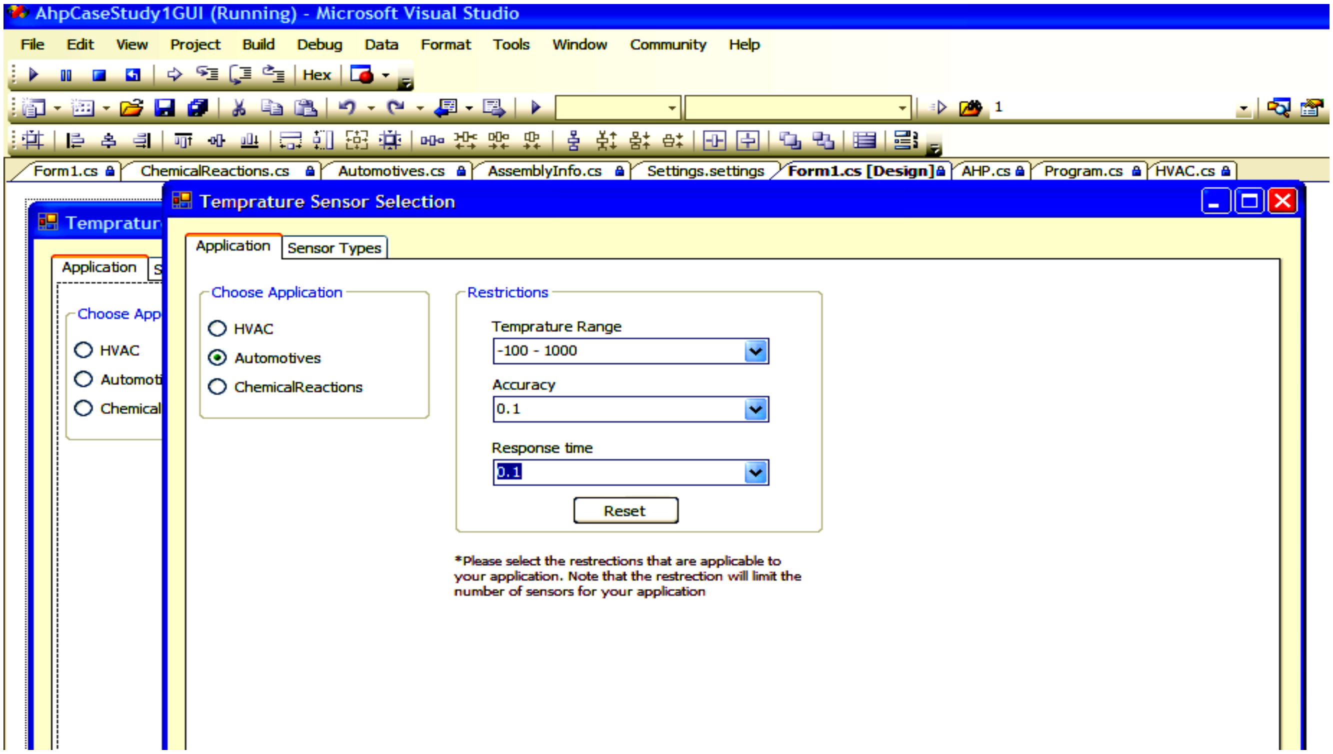


Figure 8 Selection of Automotives application and restrictions pertaining to the application in the first tab of the software

Having chosen the application and restrictions from the first tab, the user can press the second tab where available alternative candidate sensors by the software are automatically displayed, where available alternative sensors are shown in an activated checkbox mode and those that do not conform to the temperature range, accuracy and response time are excluded and shown in an inactivated checkbox. See Figure 9. At this stage, the user can further lessen the number of alternative sensors by checking in boxes of available alternative sensors. Here three sensors were chosen as a case study problem of choosing from among three alternative sensors: thermocouple, thermistor, and resistance temperature detector (RTD). See Figure 10.

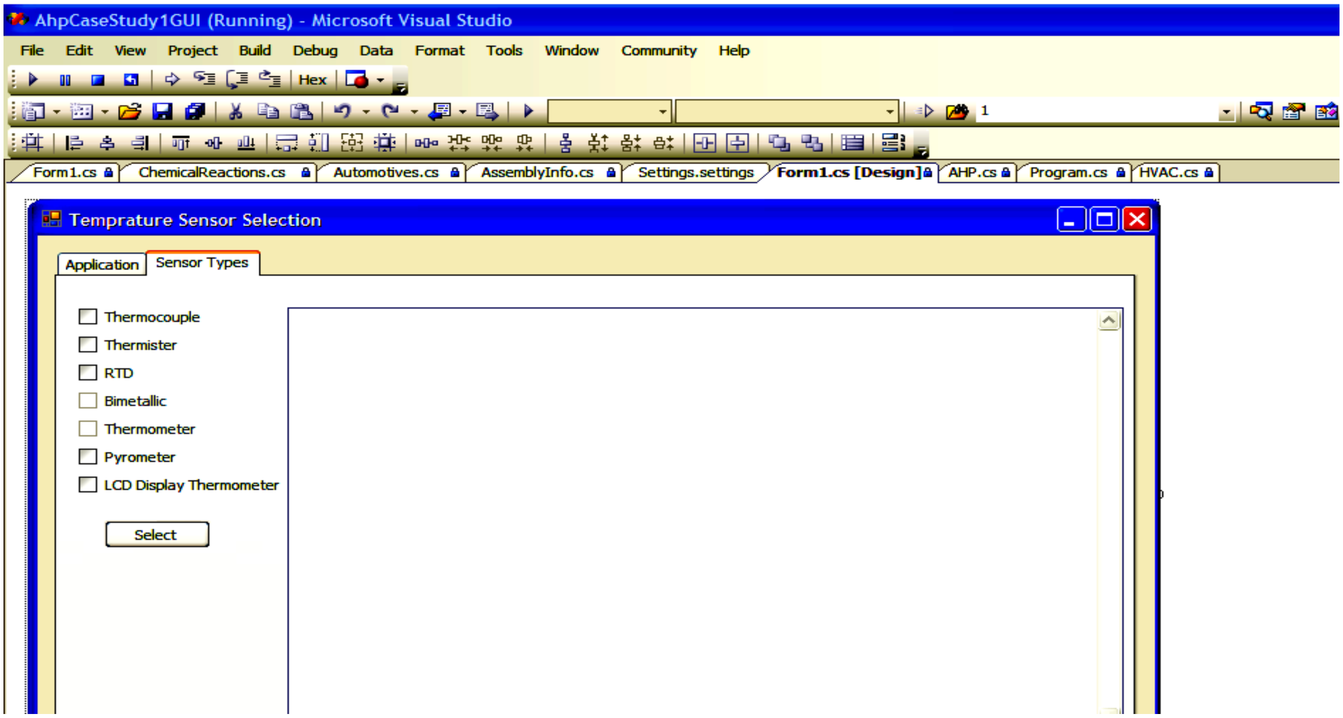


Figure 9 Second tab components. Five available candidate sensors shown in enabled checkboxes. Two excluded sensors shown in disabled checkboxes. The five available sensors can be further lessened to three sensors: thermocouple, thermistor; and RTD

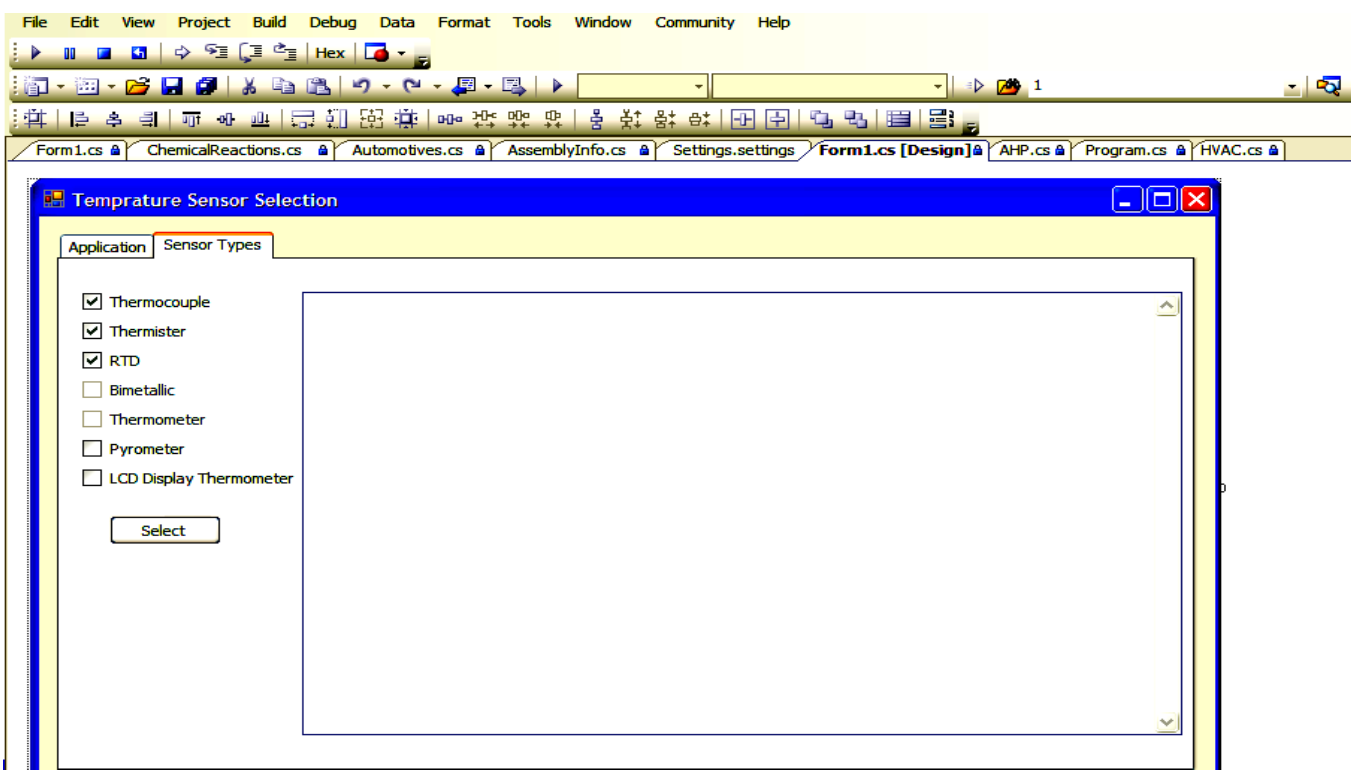


Figure 10 Three sensors are chosen for the case study: thermocouple, thermistor, and RTD

Here remains the last step exemplified in pressing the select button. Figure 11 shows the final results in terms of the final score (Ranks), the best alternative sensor based on the AHP methodology is the one with the highest Rank; the thermocouple in this case. Note the ranking of the alternatives according to numerical values, thermocouple: 0.3617659, RTD: 0.3162967, and finally in the third rank, thermistor: 0.3219372. Note also the consistency ratio associated with each pair-wise comparison matrix.

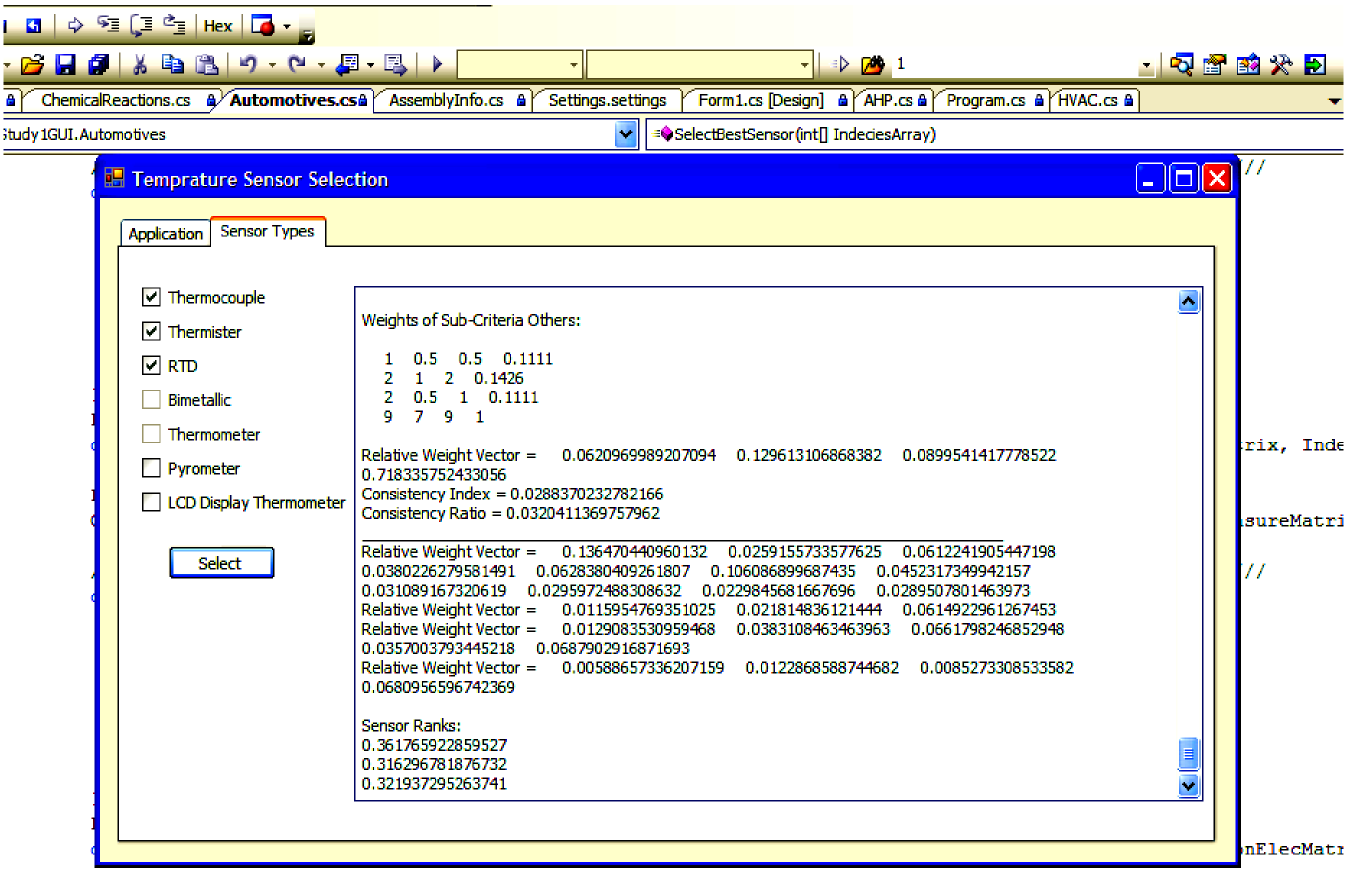


Figure 11 the final results of the software. The best alternative sensor is the one with highest rank(score), the thermocouple in this case.

4.4.2. The software calculates the weight of each sub-criterion with respect to the immediate upper level parent criterion

In this step, the system calculates the contribution of each sub-criterion towards the parent criterion. Again, by means of pair-wise comparison matrices of the sub-criteria towards the immediate parent criteria respectively. The comparison of any two sub-criteria *Ci* and *Cj* with respect to the immediate parent criterion is made using the questions of the type: of the two sub-criteria *Ci* and *Cj* which is more important and by how much. Table 2 is also used to assess these relative weights.

4.4.3 The software calculates the weight of each criterion with respect to the goal; selection of the best sensor.

The system does this by means of pair-wise comparison matrix of the criteria with respect to goal. Table 3 shows main criteria pair-wise comparison and weights with respect to the goal as a sample calculation for the three sensor selection case in Automotives application, in addition to values of consistency index and consistency ratio as appears in the computer software program.

Table 3
Pair-wise comparison of the criteria of level 2 with respect to the goal

Goal	C1	C2	C3	C4
C1	1	7.0	3.0	5.0
C2	0.1429	1.0	0.5	1.0
C3	0.3333	2.0	1.0	3.0
C4	0.2	1.0	0.3333	1.0

Consistency Index = 0.0136144360607441
Consistency Ratio = 0.0151271511786046

4.5. The software integrates the weights of the components of all levels hierarchically up to obtain the final aggregate score of each alternative sensor with respect to the goal; selection of the best sensor.

Table 4 summarizes the weights of each alternative sensor with respect to each sub-criterion as is calculated and as appears in the software console, the weights of each sub-criterion that belong to the same upper criterion with respect to this criterion, the weights of criteria with respect to the goal, the synthesis weight (value) of each sub-criterion with respect to the goal, and the synthesis weight (value) of each alternative sensor with respect to each criterion. Table 5 shows the aggregate score of each sensor with respect to each criterion, the aggregate final score of each sensor with respect to the goal, as well as the rank of the three sensors.

Table 4
Weights of sub-criteria, criteria and synthesis values for sub-criteria and the alternatives.

Criteria	Weights of Criteria	Sub-criteria	Weights of Sub-criteria	Synthesis Value	Thermocouple	Thermister	RTD
C1	0.58841	CS1	0.23193	0.13670	0.57413	0.24783	0.17804
		CS2	0.04404	0.02591	0.36147	0.09883	0.53970
		CS3	0.10405	0.06122	0.14635	0.06750	0.78615
		CS4	0.06462	0.03802	0.06225	0.70131	0.23644
		CS5	010679	0.06284	0.73695	0.07677	0.18628
		CS6	0.18029	0.10608	0.07182	0.22666	0.70152
		CS7	0.07687	0.04523	0.0679	0.80119	0.12902
		CS8	0.05284	0.03109	0.06413	0.64635	0.28952
		CS9	0.05030	0.02960	0.10434	0.76260	0.13306
		CS10	0.03906	0.02298	0.2	0.4	0.4
		CS11	0.04200	0.02471	0.06413	0.28952	0.64635
		Score of each alternative against first criterion			0.16744	0.19136	0.22550

C2	0.09490	CS12	0.12218	0.01159	0.59611	0.22899	0.17489
		CS13	0.22987	0.02181	0.35806	0.13489	0.50704
		CS14	0.64795	0.06149	0.60393	0.32578	0.07028
		Score of each alternative against second criterion			0.05185	0.02563	0.01741
C3	0.22188	CS15	0.05817	0.01291	0.59489	0.27661	0.12850
		CS16	0.17266	0.03831	0.16378	0.53896	0.29726
		CS17	0.29826	0.06618	0.65299	0.09602	0.25100
		CS18	0.16089	0.03570	0.74965	0.13259	0.11775
		CS19	0.31002	0.06879	0.08278	0.53366	0.38356
		Score of each alternative against third criterion			0.08963	0.07202	0.06025
C4	0.09479	CS20	0.06210	0.00589	0.44408	0.32220	0.23371
		CS21	0.12961	0.01229	0.13729	0.23948	0.62323
		CS22	0.08995	0.00853	0.48599	0.14238	0.37162
		CS23	0.71834	0.06809	0.64862	0.29463	0.05674
		Score of each alternative against second criterion			0.05261	0.02612	0.01607

Table 5
The aggregate weight of each sensor against each criterion, the final aggregate weight of the three sensors against the goal ,and ranking for the three sensors.

Criteria	Weights	Aggregate Weights		
		Thermocouple	Thermister	RTD
C1	0.58841	0.16744	0.19136	0.22550
C2	0.09490	0.05185	0.02563	0.01741
C3	0.22188	0.08963	0.07202	0.06025
C4	0.09479	0.05261	0.02612	0.01607
Result	Aggregate Final Score	0.36153	0.31513	0.31923
	Rank	**1**	**3**	**2**

4.6. The software performs the consistency test in terms of consistency index (CI) and consistency ratio (CR).

CR can be regarded as a measure of consistency in decision maker's comparisons. Saaty (1990) defined the consistency index (CI) as

$$CI = (\Delta_{max} - n) / (n - 1). \quad (6)$$

$$CR = CI/RI, \quad (7)$$

To calculate CR, a simple method is used by the software [16] which comprises the following four steps:

1- The software computes AW^T.
2- The software computes:

$$\sum_{i=1}^{i=n} \frac{ith\,entry\,in\,AW^T}{ith\,entry\,in\,W^T} \qquad (8)$$

3- Compute the consistency index (CI):

CI = (result in step 2 – n) / (n – 1) (9)

4- Compute Consistency ratio (CR):

$$CR = \frac{consistency\ index}{random\ index} = \frac{CI}{RI} \qquad (10)$$

The degree of consistency is satisfactory in decision maker's comparisons if CI is sufficiently small and CR $<$ .10. If CR $>$ .10, serious inconsistencies may exist, and AHP may not yield meaningful results. Values of RI for the appropriate value of *n* are given in Table 6[12]. Table 7 lists the consistency index and consistency ratio associated with all the matrices encountered by the software in the calculation of the best sensor score problem.

Table 6 Random Index Values.

n	RI
2	0
3	.58
4	.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.51

Table 7 Consistency index and ratio values encountered by the software for the automotives case study as appears by the software in the console data box .

:Maximum Operating Temprature
3 2.5 1
1.5 1 0.4
1 0.6667 0.3333
Relative Weight Vector = 0.574127972434647 0.247833007155677 0.178039020409676

Consistency Index = 0.00275870960630953
Consistency Ratio = 0.00475639587294746

____

:Minimum Operating Temprature
0.7 3.5 1
0.175 1 0.2857
1 5.7143 1.4286
Relative Weight Vector = 0.361469770111307 0.0988308783534833 0.53969935153521

Consistency Index = 0.000985857013246161
Consistency Ratio = 0.00169975347111407

:Temperature Curve
0.125 3 1
0.1111 1 0.3333
Relative Weight Vector = 0.146345658352148 0.0675044594460533 0.7861498822017991

Consistency Index = 0.0556271399475516
Consistency Ratio = 0.0959088619785373

:Maximum Sensitivity Region
0.2 0.1111 1
4 1 9
1 0.25 5
Relative Weight Vector = 0.0622511204173095 0.701310214777263 0.236438664805427

Consistency Index = 0.0361099592804857
Consistency Ratio = 0.062258550483596

:Self-Heating Issues
5 8 1
0.3333 1 0.125
Relative Weight Vector = 0.736953829051931 0.0767665162487946 0.1862796546992751 3 0.2

Consistency Index = 0.0222502851064943
Consistency Ratio = 0.0383625605284384

:Long Term Stability and Accuracy
0.125 0.25 1
0.25 1 4
1 4 8
Relative Weight Vector = 0.0718170718170718 0.226662226662227 0.701520701520701

Consistency Index = 0.0270958189921853
Consistency Ratio = 0.0467169292968712

:Typical Temperature Coefficient
0.4 0.1111 1
9 1 9
1 0.1111 2.5
Relative Weight Vector = 0.0697877304062871 0.801193769956657 0.129018499637056

Consistency Index = 0.0484013822861886
Consistency Ratio = 0.0834506591141183

:Extension Wires
0.16667 0.125 1
3 1 8
1 0.3333 6
Relative Weight Vector = 0.0641278932029313 0.646354238958575 0.289517867838493

Consistency Index = 0.0371568154825452
Consistency Ratio = 0.0640634749699056

:Long Wire Runs From Sensor
0.75 0.1429 1
6 1 7
1 0.1667 1.3333
Relative Weight Vector = 0.104344907022371 0.762596054479081 0.133059038498548

Consistency Index = 0.00107105398652974
Consistency Ratio = 0.00184664480436161

:Measurement Parameter
0.5 0.5 1
1 1 2
1 1 2
Relative Weight Vector = 0.2 0.4 0.4

Consistency Index = 0
Consistency Ratio = 0

:Temperature Measurement
0.125 0.1667 1
0.3333 1 6
1 3 8
Relative Weight Vector = 0.0641301971826562 0.289517291843562 0.646352510973782
Consistency Index = 0.0371801012039148
Consistency Ratio = 0.0641036227653703

:Stimulation Electronics Required
3 3 1
1.5 1 0.3333
1 0.6667 0.3333
Relative Weight Vector = 0.596110365822597 0.228999818643885 0.174889815533518

Consistency Index = 0.00913844690677945
Consistency Ratio = 0.0157559429427232

:Typical Output Levels Per Degree Celsius
0.75 2.5 1
0.25 1 0.4
1 4 1.3333
Relative Weight Vector = 0.358063817851437 0.134892193807242 0.507043988341321

Consistency Index = 0.00184387141247488
Consistency Ratio = 0.00317908864219808

:Typical Fast Thermal Time Constant
8 2 1
5 1 0.5
1 0.2 0.125
Relative Weight Vector = 0.603937728937729 0.325778388278388 0.0702838827838828

Consistency Index = 0.00276965702240983
Consistency Ratio = 0.00477527072829282

:Typical Small Size
5 2 1
2 1 0.5
1 0.5 0.2
Relative Weight Vector = 0.594887955182073 0.276610644257703 0.128501400560224

Consistency Index = 0.00276935034571335
Consistency Ratio = 0.00477474197536785

:Noise Immunity
0.5 0.3333 1
2 1 3
1 0.5 2
Relative Weight Vector = 0.163775705012818 0.538964344806269 0.297259950180912

Consistency Index = 0.00458599539378501
Consistency Ratio = 0.00790688860997416

:Fragility-Durability
3 6 1
0.3333 1 0.1667
1 3 0.3333
Relative Weight Vector = 0.652993228153037 0.0960164365366913 0.250990335310272

Consistency Index = 0.00918261035484158
Consistency Ratio = 0.0158320868186924

:High Thermal Gradient Environment
5 8 1
1.5 1 0.125
1 0.6667 0.2

Relative Weight Vector = 0.749655666986531 0.132595847262205 0.117748485751264

Consistency Index = 0.0438647894950075
Consistency Ratio = 0.0756289474051853

:Corrosion Resistance
0.2 0.1667 1
1.5 1 6
1 0.6667 5
Relative Weight Vector = 0.0827771246028764 0.533663422340198 0.383559453056926

Consistency Index = 0.00281277084435216
Consistency Ratio = 0.00484960490405546

:Point or Area Measurement
1.75 1.5 1
1.5 1 0.6667
1 0.6667 0.5714
Relative Weight Vector = 0.444083830098495 0.322204642110447 0.233711527791058

Consistency Index = 0.00351769252661072
Consistency Ratio = 0.00606498711484606

:Manufacturing Variances
0.25 0.5 1
0.3333 1 2
1 3 4
Relative Weight Vector = 0.137288771660022 0.239482067625818 0.62322916071416

Consistency Index = 0.00915411860679627
Consistency Ratio = 0.015782963115166

:NIST Standards
1.5 3 1
0.3333 1 0.3333
1 3 0.6667
Relative Weight Vector = 0.485996473908096 0.142381273645236 0.371622252446667

Consistency Index = 0.00913083503130641
Consistency Ratio = 0.0157428190194938

:Cost
9 3 1
7 1 0.3333
1 0.1429 0.1111
Relative Weight Vector = 0.648623733158038 0.294631591057313 0.0567446757846496

Consistency Index = 0.0406517889330609
Consistency Ratio = 0.0700892912638981

:Weights of Criteria
5 3 7 1
1 0.5 1 0.1429
3 1 2 0.3333
1 0.3333 1 0.2
Relative Weight Vector = 0.588411272893244 0.0949026091832917 0.221889695159329 0.0947964227641348

Consistency Index = 0.0136144360607441
Consistency Ratio = 0.0151271511786046

:Weights of Sub-Criteria Static
3 8 4 3 3 1 3 4 4 8 1
2 2 1 1 0.5 0.2 0.25 0.5 0.3333 1 0.125
3 3 2 3 1 0.3333 1 3 1 3 0.25
2 2 2 2 0.5 0.3333 0.3333 1 0.3333 2 0.25
2 2 2 2 2 0.5 1 3 1 4 0.3333
3 3 3 3 3 1 2 3 3 5 1
1 2 2 2 1 0.3333 0.5 2 1 2 0.3333
2 0.5 2 1 0.5 0.3333 0.5 0.5 0.3333 1 0.3333
2 2 1 0.5 0.5 0.3333 0.5 0.5 0.5 1 0.25

0.3333 1 0.5 2 0.5 0.3333 0.5 0.5 0.3333 0.5 0.125
1 3 0.5 0.5 1 0.3333 0.5 0.5 0.3333 0.5 0.3333
Relative Weight Vector = 0.231930364435578 0.0440432985424199 0.104049995921522 0.0646191358149719 0.10679272104561 0.18029379207132 0.0768709524748043 0.0528357778867019 0.0503002749851005 0.0390620799186146 0.049201606903357

Consistency Index = 0.0830489849327734
Consistency Ratio = 0.0522320659954549

Weights of Sub-Criteria Dynamic
0.2 0.5 1
0.3333 1 2
1 3 5
Relative Weight Vector = 0.122182909773401 0.229865504322558 0.647951585904041

Consistency Index = 0.00183266180847741
Consistency Ratio = 0.00315976173875415

:Weights of Sub-Criteria Environmental
0.2 0.3333 0.25 0.25 1
0.5 1 0.5 1 4
1 2 1 2 4
0.5 1 0.5 1 3
1 2 1 2 5
Relative Weight Vector = 0.0581746398212765 0.172657167872925 0.298255512216437 0.160892461990572 0.31002021809879

Consistency Index = 0.0104507223200059
Consistency Ratio = 0.00933100207143382

:Weights of Sub-Criteria Others
0.1111 0.5 0.5 1
0.1426 2 1 2
0.1111 1 0.5 2
1 9 7 9
Relative Weight Vector = 0.0620969989207094 0.129613106868382 0.0899541417778522 0.718335752433056

Consistency Index = 0.0288370232782166
Consistency Ratio = 0.0320411369757962

Relative Weight Vector = 0.136470440960132 0.0259155733577625 0.0612241905447198 0.0380226279581491 0.0628380409261807 0.106086899687435 0.0452317349942157 0.031089167320619 0.0295972488308632 0.0229845681667696 0.0289507801463973
Relative Weight Vector = 0.0115954769351025 0.021814836121444 0.0614922961267453
Relative Weight Vector = 0.0129083530959468 0.0383108463463963 0.0661798246852948 0.0357003793445218 0.0687902916871693
Relative Weight Vector = 0.00588657336207159 0.0122868588744682 0.0085273308533582 0.0680956596742369

:Sensor Ranks
0.361765922859527
0.316296781876732
0.321937295263741

---

5. Conclusions

This study presents one new addition to the multitude of Analytic Hierarchy Process (AHP) applications and fields of use. The advantage of AHP method implementation in selecting the optimum temperature sensor in a certain application is that the multi-criteria decision making process is based on objective break down of the whole decision problem into a hierarchy of multiple layers (levels) that can be further broken down into low-leveled sub-layers each of which is being given an objective weight that can be integrated through the whole hierarchy to obtain an objective evaluation of the alternative candidate sensors under study rather than the decision problem is based upon one level of assessment and is subject to subjective evaluation of the situation by decision makers and expertise in the field. This study highlighted the evaluative criteria and sub-criteria that relate to the selection of temperature sensors. Those criteria with high weights through the hierarchy can be regarded as being the most important and critical in evaluation of best candidate temperature sensors and can be lumped together in a bundle and may be used as first assessment or screening stage for the selection process in other situations. One more advantage of AHP method in the selection of temperature sensors is that it has the capability to handle quantitative as well as qualitative (verbal) judgments of the alternatives and reflect these judgments into measurable quantitative final scores when ranking the alternatives. The outcome of the study in terms of alternatives final scores not only gives a rank to the candidate alternative sensors, but also gives a quantitative measure of the degree of dominance of one alternative over the others. This dominance or preference, of say the best alternative sensor, the thermocouple in this case, and inferiority of the least preferred alternative sensor, the thermister in this case, can be further tested by means of sensitivity analysis to investigate to what degree the best alternative sensor remains dominant and the inferior sensor remains inferior. Inputs to the sensitivity analysis problem can be variations in criteria and sub-criteria weights or other new criteria that can be added to the assessment process and have significant contribution, especially if area of application differs, or old sensors that can be eliminated in favor to new generations of sensors. New versions of fabricated sensors in industry in each of the sensors categories that have superior features can also be compared. These new sensors with new features may affect the degree of dominance of the alternative sensors when pair-wise compared.

Future Work

The AHP method was used alone in this study for the purpose of evaluation of the best temperature sensor, and it was assumed that evaluative criteria and sub-criteria do not depend upon each others, i.e. are independent. However, interdependencies among criteria and sub-criteria need be checked for. If interdependencies do exist, then the AHP approach can be integrated with other approaches, such as Analytic Network Process (ANP) to account for the interdependencies. For the evaluation of the effect of qualitative criteria, or for the evaluation of missing weights of factors or weights that cannot be determined precisely, AHP method can be used in conjunction with fussy logic to yield a more powerful tool in the evaluation process. Sensitivity analysis can be applied to this study in the future to test reliability and perpetuity of dominance of the best sensor against varying judgmental criteria and or weights of those criteria. Moreover, validity of the results of this study can also be tested by statistical analysis of sample process sensors which are employed in different fields of industry and to check the sample sensors against issues like: accuracy and precision, durability and reliability, resistance to environment and drift, cost evaluation, and overall performance of the sensor, then to compare the output of the statistical analysis with output of the study.

The study opens the door to apply AHP method in selecting other types of devices in many other areas, these devices may include: chemical composition sensors, pH measurement sensors, chromatography measurement sensors, meteorological air pollution sensors, water quality measurement sensors, blood pressure and blood chemistry measurement sensors, amplifiers and signal conditioners, analog-to-digital converters, computers, sensor networks, liquid crystal displays, data acquisition and recording systems, optical recorders, PID controllers, explosion-proof instruments, smart sensors, displacement sensors, thickness measurement sensors, robotics sensing, position, location, and altitude measurement sensors, fire-alarm sensors, satellite navigation sensing, level measurement sensors, velocity measurement sensors, time and frequency measurement sensors, mass and weight sensors, strain, force, torque and power measurement sensors, acoustic measurement sensors, viscosity measurement sensors, thermal conductivity measurement sensors, heat flux and thermal imaging measurement sensors, calorimetry measurement sensors, voltage, current, power and power factor measurement sensors, electric and magnetic fields and microwave measurement sensors, photometry and radiometry measurement sensors, laser, vision and image sensors, radioactivity measurement sensors and many other applications and fields of study.

References

[1] Scott, D. M. (2008). Industrial Process Sensors. DuPont Company, Experimental Station, Wilmington, Delware, USA. CRC Press Taylor & Francis Group.
[2] C. Hagart-Alexander, 1985. Jones' Instrument Technology Volume 2, Measurement of Temperature and Chemical Composition, 4^{th} ed., Butterworth & Co. (Publishers) Ltd.
[3] Vaida, O. S., Kumar, S. (2006). Analytic hierarchy process: An overview of applications. European Journal of Operational Research; 169: 1-29.
[4] Yurdakul, M. (2004). AHP as a strategic decision-making tool to justify machine tool selection. Journal of Materials Processing Technology, 146 (3) 365-376.
[5] Hsu, P. F., Wu, C. R., & Li, Y. T. (2008). Selection of infectious medical waste disposal firms by using the analytic hierarchy process and sensitivity analysis. Waste Management; 28: 1386-1394.
[6] Chang, C. W., Wu, C. R., Lin, C. T., & Chen, H. C. (2007). An Application of AHP and sensitivity analysis for selecting the best slicing machine. Computers and Industrial Engineering; 52: 296-307.
[7] Okada, H., Styles, S.W., & Grismer, M.E. (2008). Application of the Analytic Hierarchy Process to irrigationproject improvement. Part II. How professionals evaluate an irrigation project for its improvement. Agricultural Water Management; 95: 205-210.
[8] Vavra, I., Bydzovsky, J., Falckbart, K., Tejada, J., Kopera, L., Kovakova, E., Temst, K., & Bruynseraede, Y. (2001). Fe/Cr sensor for the milliKelvin temperature range. Sensors and Actuators; 91: 177-179.
[9] Hoa, C. H., Cha, Y. H. C., Prakasha, S., Potwina, G., Doerr, H. J., Deshpandey, C. V., Bunshah, R. F., & Zellerb, M. (1995). Electrical resistance drift of molybdenum silicide yhin film temperature sensors. Thin Solid Films; 260: 232-238.
[10] Bianchi, R. A., Santos, F. V. D., Karam, J. M., Courtois, B., Pressecq, F., & Sifflet, S. (1998). CMOS-compatible smart temperature sensors. Microelectronics Journal; 29: 627-636.
[11] Han, Y., & Kim, S. J. (2008). Diode temperature sensor array for measuring micro-scale surface temperatures with high resolution. Sensors and Actuators; 14: 52-58.
[12] Winston, W. L., 1994. Operations Research. Applications and Algorithms, 3^{rd} ed., Duxbury Press. An Imprint of Wadsworth Publishing Company. Belmont, California.