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Hierarchical Decision Model (HDM) for selecting a Microcontroller (MCU) for Smart Water Meter IoT

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ABSTRACT

We're entering a new era of computing technology that many are calling the Internet of Things (IoT) and its foundation is the intelligence that embedded processing provides. Integrated Microcontroller devices, which can provide the "real-time" embedded processing is a key requirement of most IoT applications. However the task of selecting the appropriate Microcontroller for an IoT application is more difficult than it seems. Traditional microcontroller selection and management practices are inadequate.

This paper proposes a new methodology of selecting a Microcontroller for an IoT application. A hierarchical decision model (HDM) is utilized in the decision making activity and qualified expert opinions are used as measurements. There are four levels in the hierarchy: objective, criteria, sub-criteria, and alternatives. Expert panel is formed based on their background and expertise in order to minimize and balance any possible biases among the members. The criteria, sub-criteria and alternatives are evaluated and prioritized, according to their contribution to the objective, by quantifying the expert's judgments. The results are validated using Inconsistency measure for the reliability of the experts and group agreement.

The final decision from this new model will help in better selection methodology for assisting embedded designers to make the right decision and select the most suitable Microcontroller required for the design from the large pool of the Microcontrollers available in the market.

This model can be improved in any future work by including other criteria maintainability, flexibility, Scalability, adding more alternatives and more expert panels.

INTRODUCTION

The last few years have seen an explosion in Internet of Things (IoT) devices and connected products such as wireless sensors, smart meters, home automation systems and wearables. The lowered cost of components such as sensors and processors along with increasing wireless connectivity has resulted in many products being made “smart” and able to communicate with each other without human intervention. Successful products must meet often competing requirements including low power consumption, long wireless connectivity ranges and higher processing power [3].

At the heart of IoT systems is a processor unit or microcontroller (MCU) that processes data and runs software stacks interfaced to a wireless device for connectivity. Selecting the right microcontroller unit (MCU) for an application is one of the critical decisions which control the success or failure of a company. MCUs have been more complex devices since on-chip resources were added. And since the trend is toward more on-chip integration of off-chip resources to reduce system costs, the decision will become increasingly complex with time [3].

Microcontroller selection is a multi-criteria problem which includes both qualitative and quantitative factors. System requirements, availability, performance, size, reliability, maintainability, environmental constraints, support, correctness, safety, cost, manufacturer’s history and track records are the vital factors to be considered whenever a system is to be implemented using a microcontroller which is the heart of the device [1].

Embedded Designers face challenges to compare in terms of quantitative and qualitative in the absence of any mathematical model. There are a variety of steps that often embedded designers follow in order to make the right decisions and finally be capable of selecting the most appropriate Microcontroller. This paper proposes a mathematical model called Hierarchical Decision Model (HDM) in this selection process which will help the designers to identify the right components for the new or existing designs.

In this research Hierarchical Decision Model (HDM) was built in the decision making process and utilized to select the best Microcontroller for a Smart Water Meter IoT.

METHODOLOGY

Hierarchical Decision Model (HDM)

The methodology that has been used in this research is the "Hierarchical Decision Modeling (HDM)" that was introduced by Cleland and Kocaoglu in 1987 [8]. The problems are usually presented in a hierarchical structure and the decision maker is guided throughout a subsequent series of pairwise comparisons to express the relative strength of the elements in the hierarchy. The alternatives are presented, two at a time, for a measure of relative weights with respect to each other. The respondent divides 100 points between the pair to reflect his judgment of each element's relative importance in comparison with the other element of the pair. For example, if the elements of a pair are given 50 points each, it only means that both have the same importance in the respondent's judgment. It does not indicate whether they both are highly important or highly unimportant. Zero is not used in measurements to avoid computational difficulties. If one element of the pair is totally insignificant compared to the other, the respondent could assign them 1 and 99, instead of 0 and 100. The other assignments are made in a similar way. For example, if one element is three times as important as the other one, they are given 75 and 25 points [8].

HDM Model

Based on literature review and consulting with experts, an HDM model was constructed (Figure 1). The model is created using PSU ETM HDM software tool. The model is utilized in the decision making activity and qualified expert opinions are used as measurements.

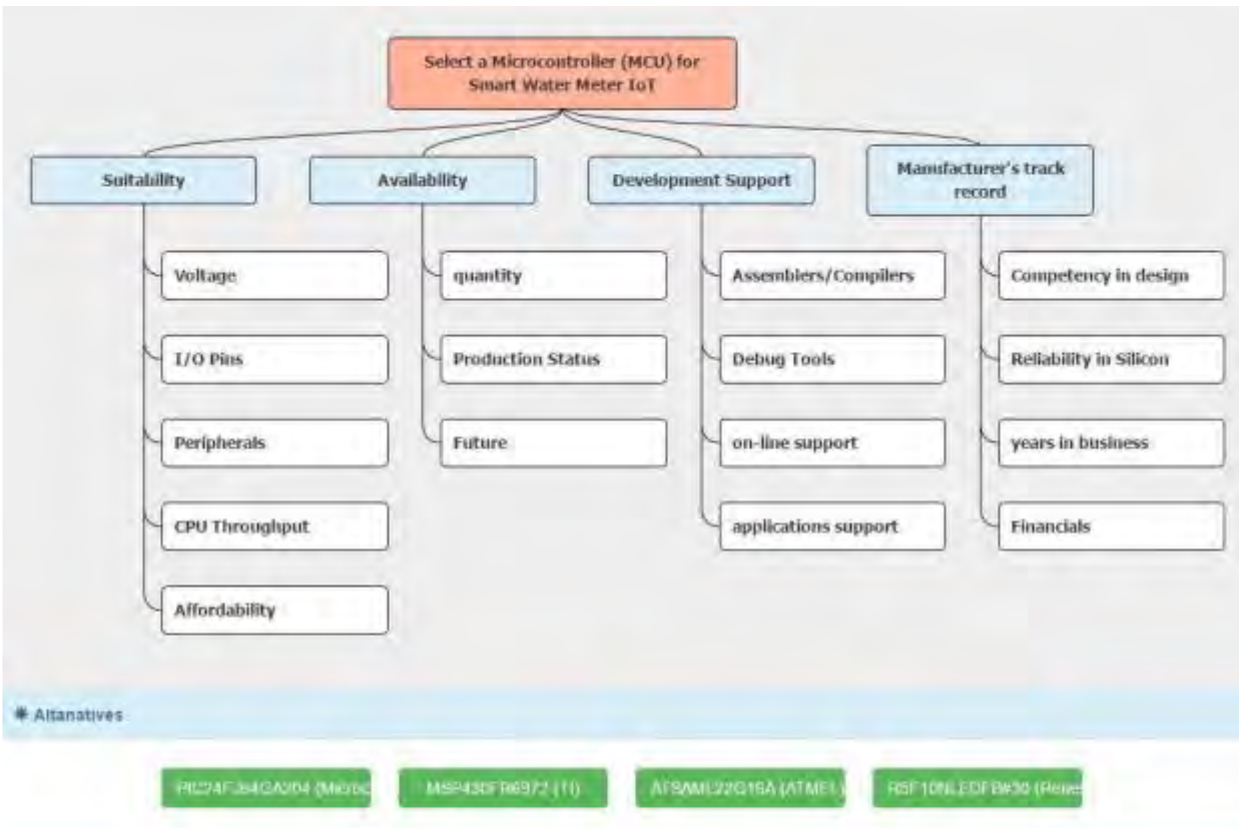

Figure1. HDM model to select a Microcontroller for Smart Water Meter IoT

There are four levels in the hierarchy: objective, criteria, sub-criteria, and alternatives. Expert panel is formed based on their background and expertise in order to minimize and balance any possible biases among the members. The criteria, sub-criteria and alternatives are evaluated and prioritized, according to their contribution to the objective, by quantifying the expert’s judgments. The results are validated using Inconsistency measure for the reliability of the experts and group agreement.

Level 1 - Objective: Select a Microcontroller for a Smart Water IoT.

Level 2 and Level 3 - Criteria and Sub-criteria: [1] [2] [3]

Suitability Perspective: Suitability of the microcontroller in terms of CPU throughput, required peripherals, I/O pins, low power and finally the cost for the smart water meter IoT system.

1. ***Voltage*:** The smart water meter sensing nodes operate on battery, so a low-power spec for an MCU is a basic requirement to minimize battery replacement [5].
2. ***I/O Pins*:** If IC of 15 I/O pins is required to develop the system there is no need to use 40 pin IC with 32 I/O pins. In this way the size of the IC can be reduced and thus physical space required to implement the system is also reduced.
3. ***Peripherals*:** One of the most important criteria that drives the MCU selection. Check for the availability of Timers, Serial interfaces, ROM, RAM, A/D converter, CRYPTO, sufficient number of I/O ports. Too many I/O ports lead to excessive cost but few cannot do the job.
4. ***CPU Throughput*:** The CPU (central processor unit) core needs to have the compute power to handle the system requirements over the life of the system for the chosen implementation language. Too much is wasteful, and too little will never work.
5. ***Affordability*:** This is the most important factor. If the system is to be implemented within the limit of the budget calculated earlier the cost of each and every component (selected MCU along with supporting ICs) used to build the system should be minimized

tactfully to fulfill the requirements. On chip features will trade with inventory and assembly cost of using extra supporting external components. They can also cut development time and effort by providing a ready integrated solution [6].

Availability Perspective: Before going to implement the system, the availability of the device should be checked. The criteria in choosing microcontroller is its ready availability in needed quantities both now and future. If sufficient quantities are available with bright future then no need to be worried about the failure of the project.

1. ***Quantity*****:** availability of sufficient quantities
2. ***Production Status*****:** Provides the status whether the MCU is in production now or still under development.
3. ***Future*****:** future availability status of the device to ensure that end of life (EOL) is not in the near future.

Development Support Perspective: During product development if the engineers face any kind of problem he/she may communicate with the marketing/sales, field application engineers. The manufacturers should have some facilities like a help line, toll free number, fax number, after-sales support, sufficient knowledgeable and helpful expertise support personnel who will give a prompt reply or they will follow through in a regular manner when they promise to do something.

1. ***Assemblers/Compilers:***
2. ***Debug Tools*****:** Evaluation module (EVM), In-circuit emulators, Logic analyzer pods, Debug monitors, Source-level debug monitors

3. ***On-line Support***: Real-time executives, application examples, Bug reports, Utility software, including "free" assemblers, sample source code.
4. ***Application Support***: Specific group who does nothing but applications support. Availability of application engineers, technicians etc and how knowledgeable are the support personnel and how truly are they interested in providing support.

Manufacturer's Track Record: The points like design challenges, on time delivery, performance, years in business, financial report should be followed as the track record of the manufacturers.

1. ***Competency in Design:*** Maturity in design and best practices
2. ***Reliability in Silicon***: Product life cycles in the industrial market are at least 10-15 years. Hence, quality, reliability and longevity requirements are key to the success of the IoT.
3. ***Years in business*** **-** Numbers of years in the business.
4. ***Financials*** **-** Financial health of the company by checking financial reports, stock performance.

Level 4 - Alternatives:

1. **PIC24FJ128GA204 from Microchip Technologies:**

PIC24F 16-bit Microcontroller featuring integrated Hardware Crypto module and extreme Low Power. This family also includes 128KB Flash, 8KB RAM and advanced peripherals. The combination of features makes the part ideally suited for low power embedded security applications [9].

2. **MSP430FR6972 from Texas Instruments:**

This ultra-low-power MSP430FRxx FRAM microcontroller family consists of several devices featuring embedded nonvolatile FRAM, a 16-bit CPU, and different sets of peripherals targeted for various applications. The architecture, FRAM, and peripherals, combined with seven low-power modes, are optimized to achieve extended battery life in portable and wireless sensing applications. FRAM is a new nonvolatile memory that combines the speed, flexibility, and endurance of SRAM with the stability and reliability of flash, all at lower total power consumption [10].

3. **ATSAML22G16A from Atmel (now Microchip Technologies):** The ultra-low-power ATSAML22 based Flash microcontrollers (MCU) feature sophisticated power management technologies. It consumes 39 µA/ MHz (CPU running CoreMark) in active mode and down to 490nA in Ultra low-power backup mode with RTC. In addition to ultra-low-power performance, these devices feature Segment LCD controller, tamper detection, smart card interface, Full Speed USB device, Event System and Sleepwalking, 12-bit analog, AES, capacitive touch sensing and much more. SMART SAM L22 is a series of Ultra low-power segment LCD microcontrollers using the 32-bit ARM® Cortex® -M0+ processor, ranging from 48- to 100-pins with up to 256KB Flash and 32KB of SSRAM and to drive up to 320 LCD segments [11].
4. **R5F10NLEDFB#30 from Renesas:** RL78/I1C microcontrollers feature integrated functions for high precision smart electricity metering, such as 24-bit Delta-Sigma A/D operation, AES H/W integration, up to 256 KB flash line-up, a 32-bit MAC (Multiply and Accumulation) function, independent power supply for RTC and enhance battery pin (Vbat) function for AC-off operation, and Hardware zero cross detection. Performance is

enhanced with a high temperature coefficient internal reference voltage. A segment LCD driver supports 8-COM [12].

DATA AND DATA SOURCE(S)

The Data was gathered from Experts Panel and extensive Literature Review in the areas of Internet of Things, Smart Water Meters, Microcontrollers, Vendor Data Sheets, Application Notes, Embedded Forums, Blogs etc.

Expert's panel

To build and evaluate the model an expert's panel was established. The expert's panel consists of five experts including the author. They have extensive experience in the Semiconductor Industry and specifically in the areas of Embedded Product Development, Smart Water Meter IoT, Microcontroller/ Microprocessor design. Expert's panel are previous colleagues of the author and worked with them on various projects in the last 18 years. Table 1 offer more details about the experts.

Expert			Semiconductor Industry Experience		
	Name	Current Position	Embedded Product Development	Smart Water Meter IoT	Microcontroller/Microprocessor Development
Expert 1	Manohar Bandarum	Founder and CEO of an IoT Startup			
Expert 2	Vikas Thukuntla	Hardware Architect			
Expert 3	Levis Li	Marketing Director - Embedded Products			
Expert 4	Murthy Hari	Engineering Director			
Expert 5	Surekha Chanamolu	Graduate Student - Program/Project Manager			

Table 1 Experts Panel

Experts were asked to evaluate the model. They were contacted via Skype Voice, Whatsapp texting app and e-mail. Clearly explained the objective and what is required of them. Then each one of them got an email with the details of the model, consolidated data from Table 6 and how to evaluate it. Finally, the experts used ETM HDM tool to evaluate the model. Experts evaluated the criteria and sub-criteria, the results section has more details about their evaluation and analysis of the results.

DATA

The Data was gathered from experts and literature review in the following areas:

- **Internet of Things (IoT):** Internet of Things is created to address the challenges of bridging the gap between the physical world and the information world [6]. Electronic devices will be able to communicate wirelessly to each other and store information on the internet. The information will be analyzed, and used to optimize various systems, making them more efficient, which in turn saves energy, time, money and lives. From a technology perspective, the IoT is being defined as smart machines interacting and communicating with other machines, objects, environments and infrastructures, resulting in volumes of data generated and processing of that data into useful actions that can "command and control" things and make life much easier for human beings[3].
- **IoT Use Cases / Applications:** The following are some of the use cases / applications under consideration[3]:
  - Machine-to-machine communication
  - Machine-to-infrastructure communication
  - Telehealth: remote or real-time pervasive monitoring of patients, diagnosis and drug delivery
  - Continuous monitoring of, and firmware upgrades for, vehicles
  - Asset tracking of goods on the move
  - Automatic traffic management
  - Remote security and control

- Environmental monitoring and control
- Home and industrial building automation
- "Smart" applications, including cities, water, agriculture, buildings, grid, meters, broadband, cars, appliances, tags, animal farming and the environment.

- **Smart Water Meter:** Water is a vital resource for human survival, conservation and management of the water resources must be given most importance. Smart water meters are electronic measuring devices that essentially perform three functions; they automatically and electronically capture, collect and communicate up-to-date water usage readings real-time for monitoring and billing [7].
- **Microcontrollers:** A microcontroller is a microprocessor that has been optimized for embedded control applications. Such applications typically monitor and set numerous single-bit control signals but do not perform large amounts of data computations. Several peripheral components common in control applications, like serial communication peripherals, timers, counters, pulse-width modulators, and analogue-digital converters are integrated in the microcontroller. This integration of peripherals enables single-chip implementations and hence smaller and lower-cost products [1].
- **Microcontroller Classification based on Architecture:** Based on the number of bits Microcontrollers are broadly classified into four different categories i.e., 4-bit, 8-bit, 16-bit and 32-bit microcontrollers. 4-bit microcontrollers are extensively used in electronic toys. 8-bit microcontrollers are generally used in various control applications such as position control, speed control and any process control system. The 16-bit

microcontroller are designed and developed for the purpose of high speed control applications. Programming of such microcontroller can be achieved either by high level programming language or by assembly language programming. [13]

- **Smart Water Meter IoT System requirements [3]**

The following figure 2 provides the functional view of IoT technologies [3]

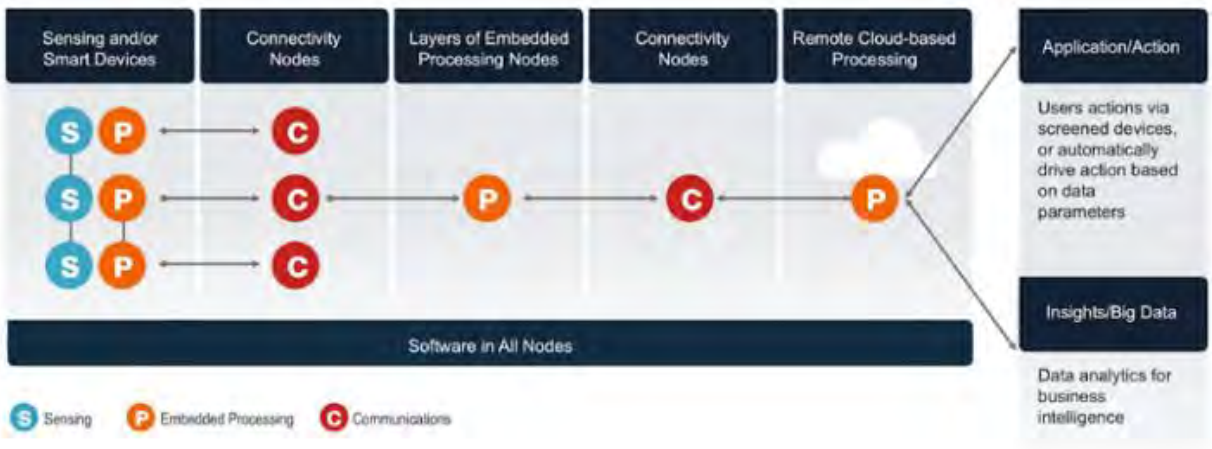

Figure 2. Functional View of IoT [3]

The following requirements are common to

- ***Sensing and data collection capability (sensing nodes)***: Flow meter sensor for smart water IoT that converts the water flow to an electrical signal, which can be accepted and processed by the MCU.
- ***Layers of local embedded processing capability (embedded processing nodes)***: Embedded processing is at the heart of the IoT and integrated MCU's that provide "real-time" embedded processing is a key requirement.
- ***Wired and/or wireless communication capability (connectivity nodes)*** - Low power RF radios are typically used to communicate between the battery-

powered water meter and either another meter in a mesh network or a data collector. Requirements for communication functions are almost the same as for MCU.

  - Cost-effectiveness
  - Low power
  - Quality and reliability
  - Security

- ***Software to automate tasks and enable new classes of services -*** Software plays a key role in connecting all segments of the IoT and making them to work together for successful rollout of technology.
- ***Remote network/cloud-based embedded processing capability (remote embedded processing nodes) -*** Accessing remote supercomputing nodes (Cloud computing) for heavy-duty data processing and analysis
- ***Full security across the signal path -*** Security of information that gets passed around by various parts of the system and Device-level security.

- **Microcontroller (MCU) Requirements for Smart Water Meter IoT[3]:**

The following block diagram (Figure 3) from TI [4] highlights the different connectivity options for an MCU in a generic flow meter topology.

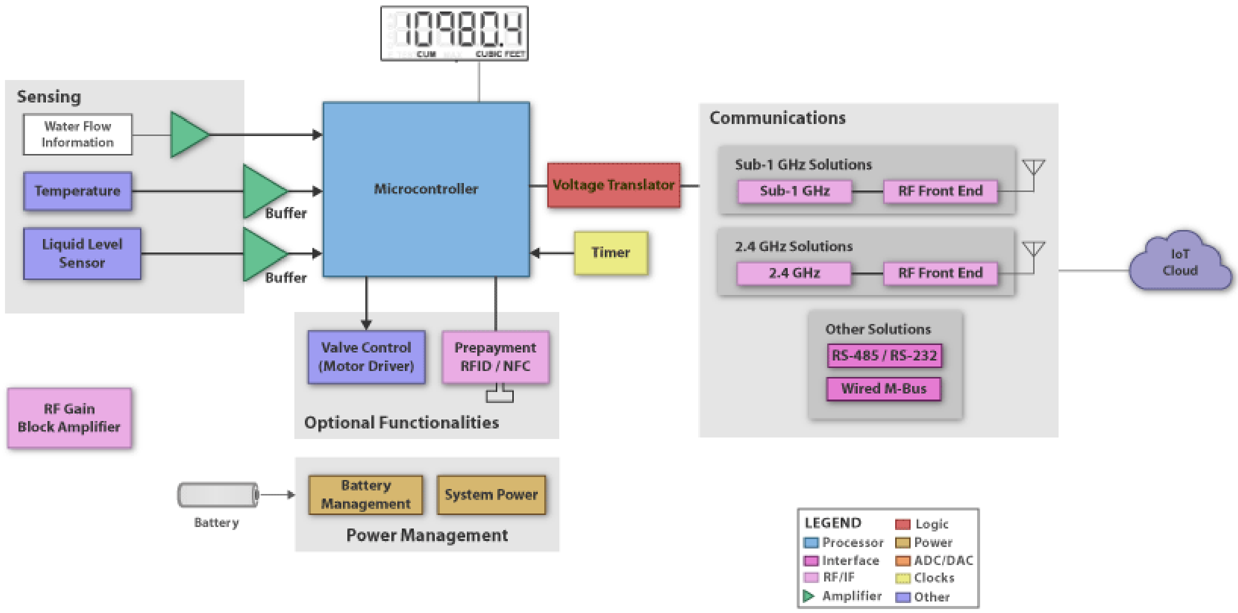

Figure3. A TI-enabled smart flow meter solution featuring various connectivity options [4]

The following are the most important

- ***Energy efficiency***: MCU needs to be energy-efficient as the sensing nodes are battery-operated satellite nodes, so a low-power spec is a basic requirement to minimize battery replacement.
- ***Embedded architecture with a rich software ecosystem:*** The MCU's supporting the IoT should provide a broad ecosystem of software development environment. The software ties together the applications, the command, control and routing processing and the security of the node and system.
- ***Portfolio breadth that cost-effectively enables different levels of performance and a robust mix of I/O interfaces***: There are so many MCU's available in the market with different tiers of devices, with diverse I/Os. Carefully choose MCU that is cost-performance-optimized for the specific application.

- ***Cost-effectiveness***: The overall product cost is a very important factor as the overall cost is the sum of the parts of the system plus the cost of the services required for the system.
- ***Quality and Reliability:*** Product life cycles in the industrial market are at least 10-15 years unlike mobile phone, laptop or other electronic device that you may change every two years. Hence, quality, reliability and longevity requirements of an MCU for these markets are keys to the success of the IoT.
- ***Security:*** For the local embedded processing node at the physical layer, there are a variety of cryptographic engines and security accelerators to support data encryption (e.g. DES, AES, etc.) and authentication (e.g. SHA, etc.).

After literature review and talking to experts

- ***Criteria and Sub-criteria:*** Conducted extensive literature research in the areas of IoT ecosystem, smart water meter IoT's, different MCU vendor's App notes, literature and, Datasheets, different semiconductors and embedded Forums, blogs etc and expert opinions for finalizing the most important criteria and factors as shown in Table 2 for selecting an MCU for Smart Water Meter IoT [1], [2], [3], [4].

Criteria	Sub-Criteria
Suitability	Voltage
	I/O pins
	Peripherals
	CPU Throughput
	Affordability
Availability	quantity
	Production Status
	Future
Development Support	Assemblers/Compilers
	Debug Tools
	on-line support
	applications support
Manufacturer's track record	Competency in design
	Reliability in Silicon
	years in business
	Financials

Table 2 Criteria and Sub Criteria for selecting an MCU for Smart Water Meter IoT

- ***Microcontroller alternatives:*** Conducted extensive literature research of different MCU vendors and their product offerings as shown in the Table 3 below [5].

MCU Manufacturers/Vendors	Products
Microchip	PIC10, PIC12, PIC16 series, PIC18 series (8-bit), PIC24, dsPIC (16-bit), PIC32MX series
Atmel (now Microchip)	AT89 series (Intel 8051 architecture) , AT90, ATtiny, ATmega, ATxmega series (AVR architecture), AT91SAM(ARMarchitecture), AVR32 (32-bit AVR architecture), MARC4
Freescale Semiconductor (now NXP)	68HC05, 68HC08, 68HC11 (8-bit), 68HC12, 68HC16 (16-bit), 683XX, MCF5xxx, M-core, MPC500, MPC860 (32-bit)
NXP Semiconductor	80C51 (8-bit), XA (16-bit), ARM7/LPC2000, ARM9/LPC3000, ARM Cortex-M0/LPC800,LPC1100, LPC1200, ARM Cortex-M3/LPC1300, LPC1700, LPC1800, ARM Cortex-M4/LPC4300
Texas Instruments	TMS370 (8-bit), MSP430 (16-bit), TMS 320, ARM Cortex-R4/TMS570 (32-bit)
Renesas	RL78 16-bit MCU; RX 32-bit MCU; SuperH; V850 32-bit MCU; H8; R8C 16-bit MCU
ST Microelectronics	ST6, ST7, STM8, uPSD (8-bit), ST10 (16-bit), ST20, ARM7/STR7, ARM9/STR9, ARM Cortex-M0/STM32 F0, ARM Cortex-M3/STM32 F1, F2, ARM Cortex-M4/STM32 F4

Table 3 List of Manufacturers and their products

Used the following guidance from Table 4 that was available from literature research and expert opinion (Expert 1 and Expert 2) in short listing the four best MCU alternatives for the decision model.

MCU Requirements for Smart Water Meter IoT
Low Power - 2.5 v - 3.6 v
16-bit Architecture
CPU Throughput - 16 Mhz or less
Flash - 64KB
RAM - 4KB
Digital Sensor Interface (Flow sensor & Temp Sensor) - GPIO with interrupt
RFE Interface - UART/I2C/SPI
Battery Interface - PWM and ADC
TIMERS
RTC
CRYPTO
UART for Debug
LCD Interface
ADC - 8 ch
Comparator
I/Os - 32 pins or 44 pins or 64 pins max with package size of 64 (max)
Operating Temp Range - -20C to 85C

Table 4 Most Important MCU requirements for Smart Water IoT

Finalized the following four best MCU alternatives as shown in Table below with product features from the following vendor's:

- PIC24FJ64GA204 from Microchip Technologies
- MSP430FR6972 from Texas Instruments
- ATSAML22G16A from Atmel
- R5F10NLEDFB#30 from Renesas

DataSheet	PIC24FJ64GA204	MSP430FR6972	ATSAML22G16A	R5F10NLEDFB#30
Status	In Production	In Production	In Production	In Production
Hardware RTCC	Yes	Yes	Yes	Yes
DMA Channels	6	3	16	
Low Power	Yes	Yes	Yes	Yes
Vbat	TRUE			
Comparators	3	8	2	
ADC Modules	1	1	1	1
Total ADC Channels	12	8	10	4
ADC Mode (bits)	12	12	12	10
ADC Mode (ksps)	500		1000	
Hardware Cap Voltage Divider (CVD)	FALSE			
Watchdog		Yes		Yes
Brown Out Reset		Yes		
IP Protection		Yes		
Multiplier		32x32		
OpAmps	0			
CTMU	Yes			
UART	4	2		3
SPI	3	4	3	
I2C	2	2	2	3
I2S	3	0		
CLC	0			
PTG	FALSE			
PPS	Yes		Yes	
# USB Modules	0		1	
# of CAN Modules	0			
LIN	No			1
IrDA	No	Yes		1
Input Capture	6		12	
Max. PWM Outputs	6			
PWM Time Bases	1			
PWM Resolution (bits)	16			
PWM Resolution (ns)	62			
Quadrature Encoder Interface (QEI)	0			
Segment LCD	0	Yes	yes	120
Temp Sensor	No	Yes		
HW Encryption	Yes	Yes	Yes	
Parallel Port	EPMP		GPIO	
Max 8bit Timers	0			4
Max 16bit Timers	5	5	4	8
eEPROM (Bytes)	2			
Temperature Min	-40	-40	-40	-40
Temperature Max	85	85	85	85
Operation Voltage Min	2	1.8	1.62	1.7
Operation Voltage Max	3.6	3.6	3.63	5.5

As a final step to help with the selection process and judgment quantification, built a table [Table 6] listing each MCU under consideration on one axis and the important criteria and sub-criteria on another axis. To obtain a fair side-by-side comparison, filled the blanks from the manufacturer's data sheets.

Criteria	Sub-Criteria		Alternatives			
			Microchip PIC24FJ64GA204	TI MSP430FR6972	Atmel ATSAML22G16A	Renessas R5F10NLEDFB#30
Suitability	Voltage		2 to 3.6	1.8 to 3.6	1.62 to 3.63	1.7 to 5.5
	I/O pins		34 (44)	51 (64)	36 (48)	35 (64)
	Peripherals	RTC	yes	yes	yes	yes
		UART	4	2	USART	3
		RAM	8	2	8	6
		DMA	6	3	16	
		Watchdog		yes		
		PWM				
		CRYPTO	yes	yes	yes	
		FLASH	64	64	64	64
		ADC - Channels	12	8	10	4
		TIMER	5	5	4	8
		IrDA		1		1
		Comparator	3	8	2	
		SPI	3	4	3	
		LCD		yes	yes	yes
		I2C	2	2	2	3
	CPU Throughput		16	16	32	24
	Affordability		2.72	2.86	2.2	2.68
Availability	quantity		1760	1000	4000	back order
	Production Status		yes	yes	yes	yes
	Future		yes	13 weeks lead time	yes	24 weeks
Development Support	Assemblers/Compilers		yes	yes	yes	yes
	Debug Tools		yes	yes	yes	yes
	on-line support		yes	yes	yes	yes
	applications support		yes	yes	yes	yes
Manufacturer's track record	Competency in design		yes	yes	yes	
	Reliability in Silicon		yes	yes	yes	
	years in business		28	87	28	14
	Financials		2.17 B	(13 B)	2.17 B	

Table 6

ANALYSIS AND KEY FINDINGS

After analyzing the HDM evaluation results, which have been collected from the expert's panel, which include five experts who have solid knowledge and long experience in the Embedded Product Development, Smart Water IoTs, Microcontrollers, it can be concluded by the final calculation results as shown in the Table in Appendix B:

Appendix B illustrates the relative weight of alternatives towards the objective. Higher weight represents more important alternative in satisfying the decision level. From the Appendix B, we can notice that "Atmel ATSAML22G16A" is the clear winner with weight of 0.28 followed by both "Microchip PIC24FJ64GA406" and "TI MSP430FR6972" based on the experts' opinions. The alternatives chosen have competing features, so the results are very tightly coupled.

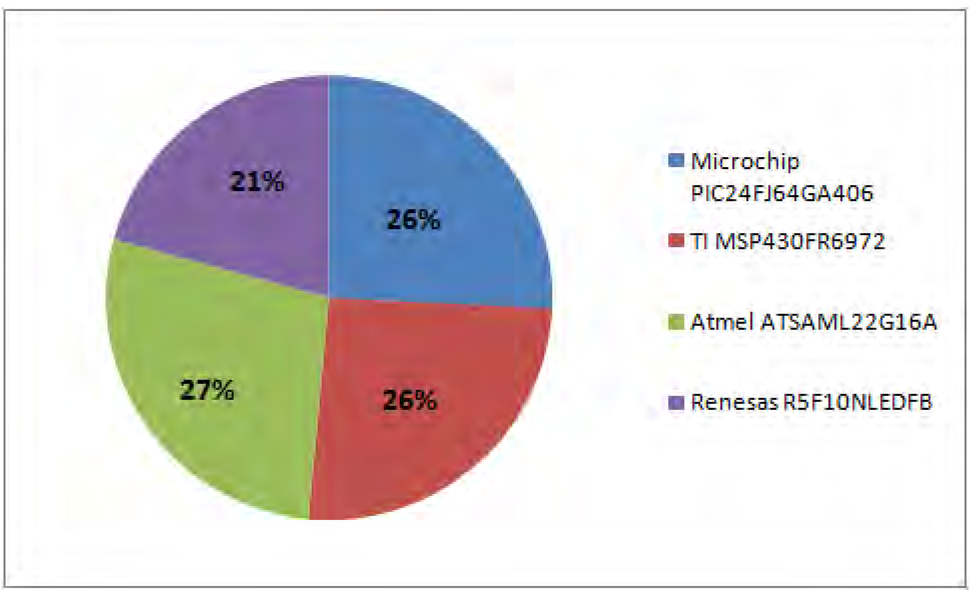

Figure 7 Amount of percentage for each alternative towards the objective

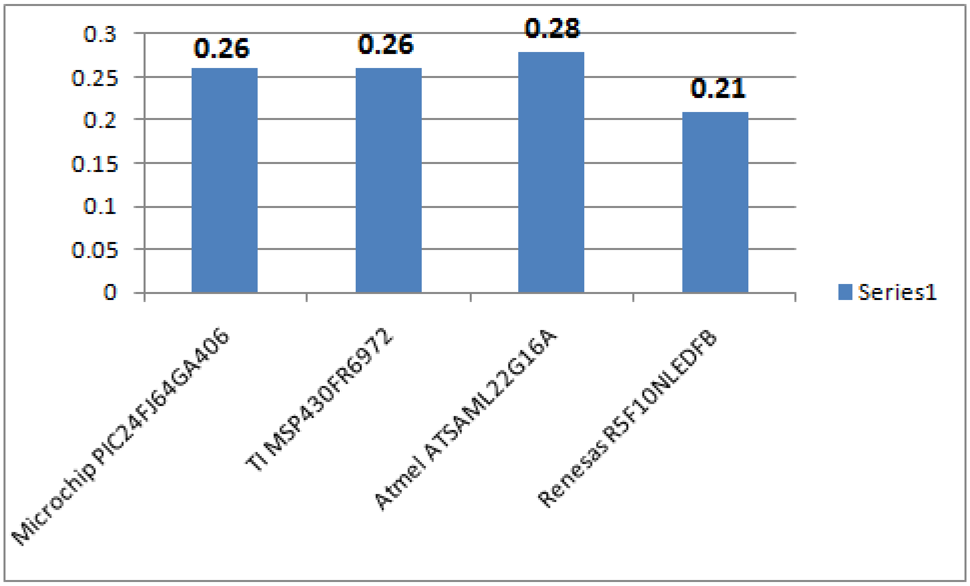

Figure 7 Relative weights of alternatives towards the objective

The inconsistency in individual expert's judgmental value is within limit. For each expert the inconsistency is < 0.1. Inconsistency Values less than 0.1 are acceptable. Disagreement is defined as the way to identify commonality among experts in pairwise comparison. A value near zero indicates that the experts were close to consensus. Lower values of both disagreement and inconsistency indicate reliable assessment. However, it is noteworthy that the data obtained from our panel of experts did not show a high disagreement value. The disagreement value shown, just 0.01, gives us a good indication that the experts are in close agreement. The disagreement and the inconsistency results highly support the model and illustrate its reliability.

FUTURE RESEARCH

Following are some of the limitations to this paper that can be addressed in future work:

- In the literature review there are many scholarly papers explaining the criteria for choosing a Microcontroller for a suitable application. But did not encounter any paper that includes a Hierarchical Decision Model or AHP for choosing the right Microcontroller for IoT System.
- Microcontrollers have so many competing requirements to consider. Even though this model tried to cover the most important criteria, but still there is room for expanding this model to even include maintainability, flexibility, Scalability etc. So these should be addressed in any future work.
- This model considered only four alternatives but even more number of alternatives can be addressed in any future work.
- This model focused on Smart Water Meter IoT. In the future this model can be either generalized or developed for other IoT applications like automotive, wearables or any other embedded applications.
- Use of multiple expert panels.
- Consider real case studies to better evaluate the reliability and robustness of the model.

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APPENDIX A – FINAL, QUANTIFIED MODEL

Computation of the average of the weights on level 1 and level 2 criteria.

Level 1	Suitability	Availability	Development Support	Manufacturer's Track Record	Inconsistency
Levis Li	0.52	0.26	0.15	0.07	0.03
MANOHAR BANDARUM	0.43	0.12	0.18	0.28	0.03
Murthy Hari	0.43	0.13	0.28	0.16	0.02
Surekha Chanamolu	0.43	0.12	0.22	0.24	0.02
Vikas Thukuntla	0.26	0.29	0.27	0.19	0.19
Mean	**0.41**	**0.18**	**0.22**	**0.19**	
Minimum	**0.26**	**0.12**	**0.15**	**0.07**	
Maximum	**0.52**	**0.29**	**0.28**	**0.28**	
Std. Deviation	**0.09**	**0.08**	**0.06**	**0.08**	

Table: Level 1 Objective

Level 2 - Suitability	Voltage	I/O pins	Peripherals	CPU Throughput	Affordability
Levis Li	0.06	0.17	0.35	0.21	0.22
MANOHAR BANDARUM	0.09	0.3	0.3	0.18	0.13
Murthy Hari	0.17	0.14	0.29	0.1	0.3
Surekha Chanamolu	0.24	0.13	0.35	0.14	0.14
Vikas Thukuntla	0.2	0.14	0.31	0.27	0.08
Mean	**0.15**	**0.18**	**0.32**	**0.18**	**0.17**
Minimum	**0.06**	**0.13**	**0.29**	**0.1**	**0.08**
Maximum	**0.24**	**0.3**	**0.35**	**0.27**	**0.3**
Std. Deviation	**0.08**	**0.07**	**0.03**	**0.07**	**0.09**

Table: Level 2 Criteria - Suitability

Level 2 - Availability	Quantity	Production Status	Future
Levis Li	0.38	0.46	0.16
MANOHAR BANDARUM	0.08	0.1	0.82
Murthy Hari	0.13	0.28	0.59
Surekha Chanamolu	0.17	0.27	0.56
Vikas Thukuntla	0.33	0.43	0.25
Mean	**0.22**	**0.31**	**0.48**
Minimum	**0.08**	**0.1**	**0.16**
Maximum	**0.38**	**0.46**	**0.82**
Std. Deviation	**0.13**	**0.14**	**0.27**

Table: Level 2 Criteria - Availability

Level 2 - Development Support	Assemblers/ Compilers	Debug Tools	On-line support	Applications support
Levis Li	0.43	0.29	0.08	0.19
MANOHAR BANDARUM	0.17	0.36	0.19	0.27
Murthy Hari	0.09	0.28	0.32	0.32
Surekha Chanamolu	0.16	0.3	0.27	0.27
Vikas Thukuntla	0.22	0.2	0.27	0.3
Mean	**0.21**	**0.29**	**0.23**	**0.27**
Minimum	**0.09**	**0.2**	**0.08**	**0.19**
Maximum	**0.43**	**0.36**	**0.32**	**0.32**
Std. Deviation	**0.13**	**0.06**	**0.09**	**0.05**

Table: Level 2 Development Support

Level 2 - Manufacturer's Track Record	Competency in design	Reliability in Silicon	Years in business	Financials
Levis Li	0.39	0.31	0.12	0.19
MANOHAR BANDARUM	0.22	0.32	0.17	0.3
Murthy Hari	0.22	0.24	0.1	0.44
Surekha Chanamolu	0.27	0.3	0.16	0.27
Vikas Thukuntla	0.29	0.36	0.19	0.16
Mean	**0.28**	**0.31**	**0.15**	**0.27**
Minimum	**0.22**	**0.24**	**0.1**	**0.16**
Maximum	**0.39**	**0.36**	**0.19**	**0.44**
Std. Deviation	**0.07**	**0.04**	**0.04**	**0.11**

APPENDIX B – AHP/HDM PCM DATA TABLES

The following table is the final result of the online HDM Tool for the decision model.

Objective	Microchip PIC24FJ64GA406	TI MSP430FR6972	Atmel ATSAML22G16A	Renesas R5F10NLEDFB	Inconsistency
Levis Li	0.25	0.28	0.27	0.2	0.02
MANOHAR BANDARUM	0.26	0.26	0.27	0.21	0.01
Murthy Hari	0.27	0.25	0.29	0.19	0.02
Surekha Chanamolu	0.25	0.24	0.28	0.22	0.01
Vikas Thukuntla	0.25	0.25	0.28	0.22	0.01
Mean	**0.26**	**0.26**	**0.28**	**0.21**	
Minimum	**0.25**	**0.24**	**0.27**	**0.19**	
Maximum	**0.27**	**0.28**	**0.29**	**0.22**	
Std. Deviation	**0.01**	**0.01**	**0.01**	**0.01**	
Disagreement					**0.01**

Table 1 Relative Value of each alternative towards the objective