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Conversion of Control Unit Software towards AUTOSAR Compliance

MASTER'S THESIS

to achieve the university degree of

Diplom-Ingenieur

Master's degree programme: Information and Computer Engineering

submitted to

Graz University of Technology

Supervisor

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Graz, October 2019

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The work in this thesis has been sponsored by Dept. of Powertrain Controls, AVL List GmbH and has been carried out under the joint supervision by AVL and Embedded Automotive Systems Group, ITI, Graz University of Technology. Their support is hereby greatly acknowledged.

Abstract

AUTomotive Open Standard ARchitecture (AUTOSAR) consortium has been set-up to promulgate a common standard in software development across the automotive industry. AUTOSAR proposes a unique layered architecture for automotive software and a unique software development methodology. These AUTOSAR principles have been increasingly adopted for the native software development in the automotive industry. While AUTOSAR methodology generally involves the development of software from scratch, the question of whether an existing non-AUTOSAR software can be converted to AUTOSAR format has also been of greater interest to the automotive companies. This thesis investigates an approach to convert a non-AUTOSAR AVL Hybrid Control Unit (HCU) software towards AUTOSAR compliance. Firstly, the deviations of the AVL HCU software from the AUTOSAR standard have been studied across the V-Model flow of Software Development Lifecycle (SDLC). Secondly, in the conversion phase, MATLAB scripts were developed to handle the conversion and code generation process of Application Software (ASW) models to AUTOSAR format. The original Basic Software (BSW) of AVL HCU software has been reused for integration. A separate generator script has also been implemented in MATLAB for the generation of the interfacing Run Time Environment (RTE) portion. Thirdly, in the integration phase, a total of four versions of AUTOSAR compliant HCU software with different optimization settings have been generated. In the next step, the generated AUTOSAR software versions have been evaluated on a Hardware-in-the-Loop (HIL) set-up. To compare the AUTOSAR versions to the non-AUTOSAR versions, Key Performance Indicators (KPIs) such as memory consumption, task runtime, CPU utilization, and stack usage, etc. have been evaluated. To conclude, the degree of compliance of this direct conversion approach towards the AUTOSAR standard is discussed.

Keywords: AUTOSAR, Application Software, Basic Software, Run Time Environment, Task runtime, CPU utilization, Memory consumption, Stack usage

Kurzfassung

Das AUTomotive Open Standard ARchitecture (AUTOSAR) Konsortium wurde gegründet, um einen gemeinsamen Standard in der Softwareentwicklung in der gesamten Automobilindustrie zu etablieren. AUTOSAR bietet eine einzigartige Schichtenarchitektur für Automobilsoftware und eine einzigartige Softwareentwicklungsmethodik. Diese AUTOSAR-Prinzipien wurden zunehmend für die native Softwareentwicklung in der Automobilindustrie übernommen. Für die Automobilunternehmen ist es aber auch von großem Interesse, ob bestehende Legacy Software auf die AUTOSAR-Methodik umgewandelt werden kann, da AUTOSAR in der Regel nur die Entwicklung von Grund auf neuer Software umfasst. Diese Arbeit untersucht einen Ansatz zur Umwandlung einer nicht-AUTOSAR AVL Hybrid Control Unit (HCU) Software in Richtung AUTOSAR Compliance. Zuerst wurden die Abweichungen der AVL HCU-Software vom AUTOSAR-Standard über den V-Modellfluss des Software Development Life-Cycle (SDLC) untersucht. Danach wurden in der Konvertierungsphase MATLAB-Skripte entwickelt, um den Konvertierungs- und Codegenerierungsprozess von Application Software (ASW)-Modellen in das AUTOSAR-Format zu steuern. Für die Integration wurde die ursprüngliche Basic Software (BSW) der AVL HCU-Software verwendet und für die Erstellung der Schnittstelle zum Run Time Environment (RTE) wurde in MATLAB ein separates Generatorskript implementiert. Weiters wurden in der Integrationsphase insgesamt vier Versionen AUTOSAR-konformer HCU-Software mit unterschiedlichen Optimierungseinstellungen aus dem Build-Prozess generiert. Drittens wurden in der Integrationsphase insgesamt vier Versionen AUTOSAR-konformer HCU-Software mit unterschiedlichen Optimierungseinstellungen erstellt und im nächsten Schritt wurden die erzeugten Versionen auf einem Hardware-in-the-Loop (HIL)-Aufbau evaluiert. Um die AUTOSAR-Versionen mit den nicht-AUTOSAR-Versionen zu vergleichen, wurden wichtige Leistungsindikatoren wie Speicherverbrauch, Task-Laufzeit, CPU-Auslastung und Stack-Auslastung usw. ausgewertet. Abschließend wird der Konformität des benutzten direkten Konvertierungsansatzes mit dem AUTOSAR-Standard diskutiert.

Schlüsselwörter: AUTOSAR, Application Software, Basic Software, Run Time Environment, Task-Laufzeit, CPU-Auslastung, Speicherverbrauch, Stack-Nutzung

Acknowledgments

Foremost, I am greatly indebted to my mentor at AVL, Bhargav for being continuous support and motivation throughout the course of the work. I would also like to extend my deepest gratitude to my supervisor at TU Graz, Prof. Dr. Marcel Baunach for his invaluable guidance and feedback throughout this research. I am also extremely grateful for my second supervisor Tobias for reviewing the thesis and for the practical suggestions with regard to the thesis writing.

I gratefully acknowledge the assistance of my AVL colleagues, especially Ismar and Christoph Kreuzberger for their technical advice and useful suggestions for the implementation part. Many thanks to Christoph Fuerst for his invaluable insights into AUTOSAR concepts. Thanks also to Sundar and Stepan for their support with HIL validation. I am also very much grateful to Patrick for the opportunity of pursuing this research at the Powertrain Controls Dept., AVL.

Last but not least, thanks to my family and my friends who had been the constant source of support and encouragement throughout my studies. A special mention also to Mr. Kumar and Mr. Murugan for their constant encouragement to pursue masters.

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Graz, Austria, October 2019

Credits

- I would like to thank Taylor and Francis Group LLC for their permission to use Figures 2.1, 2.3 and 3.13.
- I would like to thank AUTOSAR for their permission to use Figures 2.4, 2.5, 3.3 and 3.5.

Contents

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List of Abbreviations

ADD	Automotive Data Dictionary
API	Application Programming Interface
ARXML	AUTOSAR Extensible Markup Language
ASAM	Association of Standardization of Automation and Measuring Systems
ASW	Application Software
AUTOSAR	Automotive Open System Architecture
BSS	Basic Software Scheduler
BSW	Basic Software
CAN	Controller Area Network
CIL	Customer Interface Layer
COM	Communication stack
CRC	Cyclic Redundancy Check
DCM	Diagnostic Communication Manager
DDS	Data Declaration System
ECU	Electronic Control Unit
HCU	Hybrid Control Unit
HIL	Hardware-in-the-Loop
I/O	Input/Output
ICC	Implementation Conformance Class
KPI	Key Performance Indicator
LIN	Local Interconnect Network
MBD	Model Based Development
MIL	Model-in-the-Loop
NEDC	New European Driving Cycle
NvM	NVRAM Manager
NVRAM	Non Volatile Random Access Memory
OEM	Original Equipment Manufacturer
OS	Operating System

OSEK	Open Systems and their Interfaces for the Electronics in Motor Vehicles
PDU	Protocol Data Unit
RPM	Rotation Per Minute
RTE	Run Time Environment
RTOS	Real Time Operating System
SDLC	Software Development Life-Cycle
SWC	Software Component
TLC	Target Language Compiler
VFB	Virtual Function Bus
XML	Extensible Markup Language

1. Introduction

1.1 Need for Standards

> *"Standards should be based on the consolidated results of science, technology, and experience, and aimed at the promotion of optimum community benefits."* ([1], p.12)

During the late 21st Century, there has been a growing demand for safety features, comfort and performance parameters among the car users. The advent of computerized Electronic Control Units (ECUs), electronic sensors, and actuators have ensured that these requirements can be successfully incorporated in a vehicle. Nevertheless, the volume of features added in a vehicle multiplies with every new release. This imposes additional constraints in terms of space complexity and the scaling of the ECU capacity [2]. A possible way to ensure the scalability of ECUs is to standardize the software to provide for additional functionalities. Owing to the distributed nature of tasks and the variety of engineering fields involved in the manufacturing process of an automobile, apart from the Original Equipment Manufacturers (OEMs) various automotive part suppliers, ancillaries and service providers are also associated with the product development of an automobile. A common standard in methodology and the business development process was also necessary to facilitate better collaboration and process synchronization among these conglomerates [2]. Further, in order to make sustainable utilization of resources and to drive cost efficiency throughout the manufacturing process, automotive companies increasingly preferred reusability of software and methodologies from the previous projects instead of beginning the work from scratch for the new projects.

The initial development methodologies followed in the OEMs have been on one to one basis and diversified, where ECUs were developed for specific functionalities, and the development activities were outsourced across various third party companies [2]. As mentioned in [2], this posed a major problem during the integration of ECUs in the vehicle system, when different ECUs followed different proprietary implementations, and also in the collaboration with the different automotive part suppliers throughout the development process. Additionally, the proprietary development process increasingly failed to address the long term problems such as the growing cost of development and quality requirements [2]. In order to move on from the shortcomings of proprietary methodologies,

standardization in the development methodology has now become a matter of utmost importance in the automotive industry.

1.2 Establishment of AUTOSAR Consortium

AUTOSAR has been established as a common standard in automotive software architecture and development methodology. Having been set up in 2003, the AUTOSAR consortium consists of several partner companies as shown in Figure 1.1. The setting of such a standard proves to be beneficial not only in software engineering aspects but also towards homogeneity in the business development process and ease of interaction among the suppliers and the OEMs, where the concept of Model Based Development (MBD) is in practice right from concept definition to system integration. The development of the AUTOSAR standard has aimed at fulfilling the following objectives, as per [2, 3]:

- Ensuring scalability to different version releases.
- Efficient project planning and a smooth development process.
- Encouraging reuse of software modules.
- Driving cost efficiency throughout the development process.
- Sustainable resource utilization.
- Promising important safety requirements and availability.
- Ensuring transferability of functionalities across the ECUs within a vehicle environment.
- Providing for software maintainability and upgradability throughout the life cycle of the product.

The higher level of abstraction in the layer-based AUTOSAR software architecture also reduces inter-dependencies among the layers in the software development. The application developer, in this case, can focus only on functional development without much knowledge on the internal system behaviour. Therefore, the AUTOSAR standard is envisioned as a prospective solution, that could lay the road for the OEMs to "compete" only on the quality of the "implementation" without caring much about the developmental roadblocks [2].

1.3 Problem Statement and Motivation

As the AUTOSAR standard has been concretely established, the automotive companies have been gradually migrating towards AUTOSAR over the last decade. While it is true that AUTOSAR proposes a more seamless and unique software development methodology, there has been no direct solution to convert a non-AUTOSAR software to AUTOSAR compatible software. Hence, researches have also increasingly focused on migrating legacy software to AUTOSAR architecture. In this way,

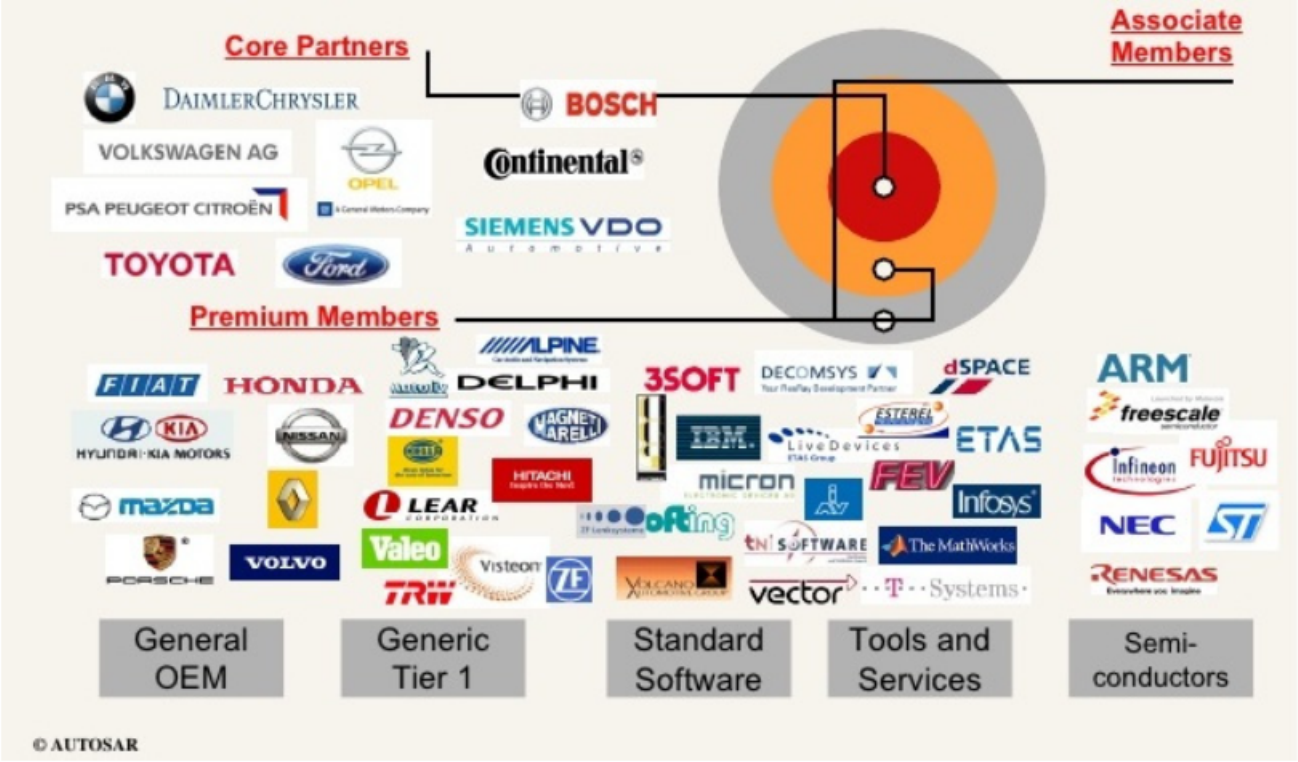


Figure 1.1: AUTOSAR partnership [4].

it would pave way for the automotive industries to reuse their proprietary legacy software models for AUTOSAR requirements rather than setting up the AUTOSAR projects from scratch.

This thesis investigates the conversion of the AVL Hybrid Control Unit (HCU) software towards AUTOSAR compliance by reusing the original software modules. The work was undertaken at the Dept. of Powertrain Controls, AVL List GmbH in association with Institute of Technical Informatics, Graz University of Technology. The conversion steps towards AUTOSAR compliance have been investigated in this work by pointing out the differences with respect to AUTOSAR specifications and methodologies at each and every level of software development. The outcome of this work shall also be a complete workflow of software conversion, including toolchains and work packages involved, which can be useful for customer projects. Besides, this thesis also emphasizes the incorporation of automation features in the ASW model conversion to AUTOSAR format with the intention of reducing manual effort in the conversion process. In conclusion, the degree of conformance of the converted software to AUTOSAR standard and the evaluation parameters such as task runtime, CPU usage, and memory consumption have also been comparatively analyzed with that of

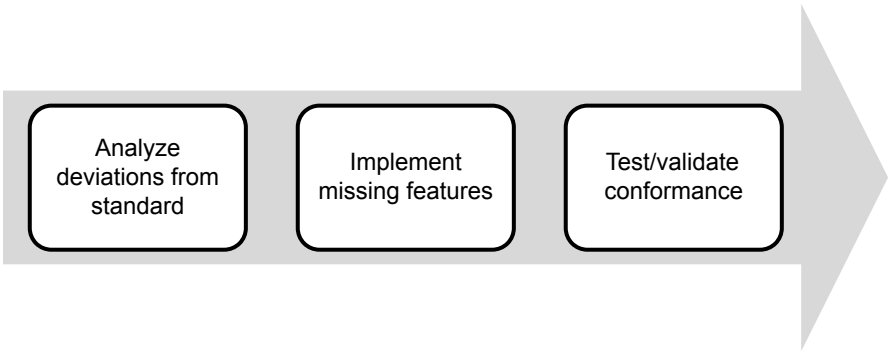


Figure 1.2: Process flow of conversion towards a standard.

the original AVL HCU software.

A generic process flow of conversion towards a standard involves three primitive steps, as shown in Figure 1.2: analysis of deviation from the standard; implementation of the observed deviations and; the test of conformance with respect to the standard. Keeping the same process flow in mind, the conversion of the HCU software towards AUTOSAR compliance, in our case, has been realized by setting the following objectives:

- Identification of deviations from the AUTOSAR standard.
- Definition of conversion methodologies towards AUTOSAR compliance including work packages and toolchains involved.
- Implementation of the missing features of compliance.
- Evaluation of Key Performance Indicators (KPIs) and validation of software in Hardware in the Loop (HIL) setup.

The first step involves the identification of deviations from the AUTOSAR standard in the original AVL HCU software. In the case of AVL projects, the BSW is procured from Tier 1 supplier companies. The primary objective in this phase is to identify deviations with regard to AUTOSAR compliance and document these deviations appropriately. In Step 2, a distinct methodology and the process workflow with regard to the conversion step have to be clearly defined. This also includes the definition of suitable work packages and the toolchains which facilitate conversion to AUTOSAR standard. The subsequent step involves the conversion of ASW models to AUTOSAR format and integration with the BSW. The interfacing RTE portion is also generated in this phase. In the final phase, once the missing features are implemented, the performance of the software with respect to metrics such as memory consumption and execution time, etc. have to be analyzed. The software is subsequently validated on a HIL setup, and the performance metrics are measured in the real ECU.

1.4 Related Work

This section describes some research works already published in the field of migration from legacy implementation to AUTOSAR and their relevance to this thesis. Comparisons are also made with some related works from other areas in the embedded systems domain.

An approach for the conversion of legacy software to AUTOSAR architecture has been presented by Daehyun et al. [5]. The authors propose some concepts of migration including allocation of the application software entities among various AUTOSAR Software Component (SWC) types and apply them to a simple legacy software model for the interior lighting system. Although the authors mention some conditions on BSW reusability, only a new BSW stack specific to AUTOSAR has been configured and used in their case-study for integration with the AUTOSAR ASW. Moreover, the possibility of automating the conversion process to AUTOSAR has not been covered in this work. This is necessary in the case of the ECU software system involving a higher number of related software models. The work in this thesis, in contrast, investigates the likelihood of BSW reusability mentioned in the work by Daehyun et al. Additionally, due to vastness of the AVL HCU software system comprising of about 40 software models, the possibility of using the automated features provided by tools such as MATLAB has also been examined for ASW conversion.

The work by James et al. [6] uses SystemDesk tool from dSPACE to automate the conversion from legacy software to AUTOSAR system. The authors use MATLAB scripting to convert ASW models to AUTOSAR format and eventually apply native Python Application Program Interfaces (APIs) from SystemDesk for system architecture modelling and RTE generation. However, owing to the non-availability of SystemDesk license, we chose to use automation features provided by MATLAB for ASW conversion in this thesis. Additionally, a separate RTE generator engine has been implemented in MATLAB M-Script based on the work by Shiquan et al. [7].

Furthermore, none of the works described above focused on the handling of calibration and measurement variables in the AUTOSAR environment during conversion. The proper handling of calibration and measurement variables is necessary when a software system involving a higher number of complex models is subjected to AUTOSAR conversion. In this thesis, the Parameter SWC type specified in the AUTOSAR standard ([8], p.34) has been used for handling the calibration variables.

Due to the relevance with AUTOSAR, some works in the topics of OSEK[1] migration have also been considered here. Denil et al. in [9] use wrappers to migrate a legacy Real Time Operating System (RTOS) application to OSEK platform. Jochen and David in [10] clearly bring out the relationship of the OSEK standard with AUTOSAR and conclude that the migration from OSEK to AUTOSAR is just the addition of the extended concepts. In our case, a modification in the OS of

[1]Open Systems and their Interfaces for the Electronics in Motor Vehicles (OSEK) [11] is a previously established automotive software standard. The AUTOSAR system service specifications are based on OSEK Operating Systems (OS) concepts. The AUTOSAR OS is considered an extended version of the OSEK OS [10].

AVL HCU software is not required since the OS implemented by the BSW supplier is already compliant with OSEK [12]. However, it must be noted here that the BSW as a whole is not AUTOSAR compliant due to reasons mentioned in Section 2.2.4.

The following are some of the works referred from other domains in embedded systems in topics related to migration. William in [13] discusses various aspects of migrating a legacy application to the Linux platform. The author additionally mentions that there is no direct conversion step in this regard and each feature of the legacy RTOS application must be mapped with its corresponding feature in the Linux OS. Another example of software migration is the work by Franck et al. [14], where the authors use an automation framework to migrate a banking application software from one platform to the other. In contrast to the above discussed works, the work in this thesis does not focus on migration from one source platform to another target platform in its entirety, but rather deals with the incorporation of AUTOSAR concepts of data access and interfacing (the RTE function calls) at the application software level without actually changing the execution platform (the BSW and the microcontroller hardware).

1.5 Thesis Structure

The rest of the thesis is structured as follows:

1. **Chapter 2** provides a brief overview of AUTOSAR layered architecture and AVL HCU software architecture.
2. **Chapter 3** presents various findings in the AUTOSAR compliance deviation analysis studied across the V-Model phases.
3. **Chapter 4** explores the implementation decisions and infers on the AUTOSAR conversion approach followed in this thesis.
4. **Chapter 5** explains the automation scripts developed for ASW conversion, RTE generation, and the build process.
5. **Chapter 6** describes the experimental setup and the results of the evaluation.
6. **Chapter 7** concludes the findings in this thesis and provides some recommendations for future works.

2. Overview of AUTOSAR and AVL HCU Software Architecture

This chapter presents a general overview of AUTOSAR software architecture and a description of each of its layers. Additionally, a description of the AVL HCU software architecture is also provided. The AUTOSAR concepts covered in this section are primarily based on AUTOSAR Release Specifications 4.3, Classic Platform.

2.1 AUTOSAR Layered Architecture

A model of software architecture has been proposed by the AUTOSAR standard for ECU development. The AUTOSAR software architecture is layered in structure and can basically be divided into three layers hierarchically as: Application Software (ASW), Run Time Environment (RTE), and Basic Software (BSW). An overview of the AUTOSAR layered software architecture is shown in Figure 2.1. Although the functionality of each layer is unique in nature, the layers function cooperatively to realize the task of the ECU system. The ASW is the functional part, wherein the functional aspects of the system are implemented. The BSW forms the core of the system and provides the Operating Systems (OS) and other services to the upper layers. The RTE actuates the dynamic behaviour of the system. The primary purpose of this layer is to support inter- and intra-ECU communication and also to interface the application (ASW) and core (BSW) part of the ECU software.

The three basic layers are bundled in such a way that the ASW is completely abstracted from the BSW by the RTE and that the application Software Components (SWCs) are not allowed to interact with the BSW modules directly, but only via the RTE [2]. The following sections present a rather detailed account on each layer in specific.

2.1.1 Application Software

As pointed earlier, the ASW portion of the software houses the functional part of the ECU software. The ASW, however, is not coded as a single program implementing all the functionalities required for the ECUs. It is rather compartmentalized into dedicated SWCs, wherein each SWC is a piece of

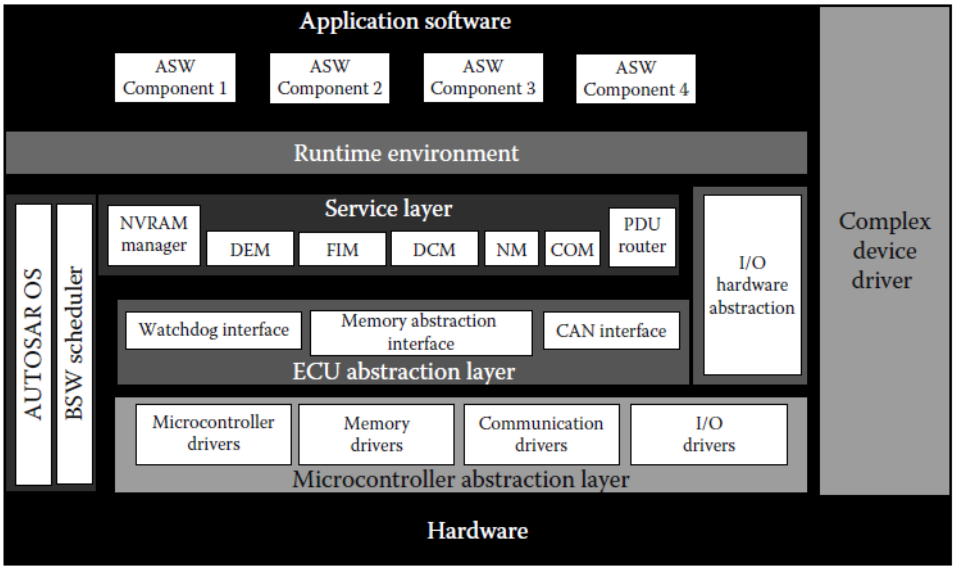
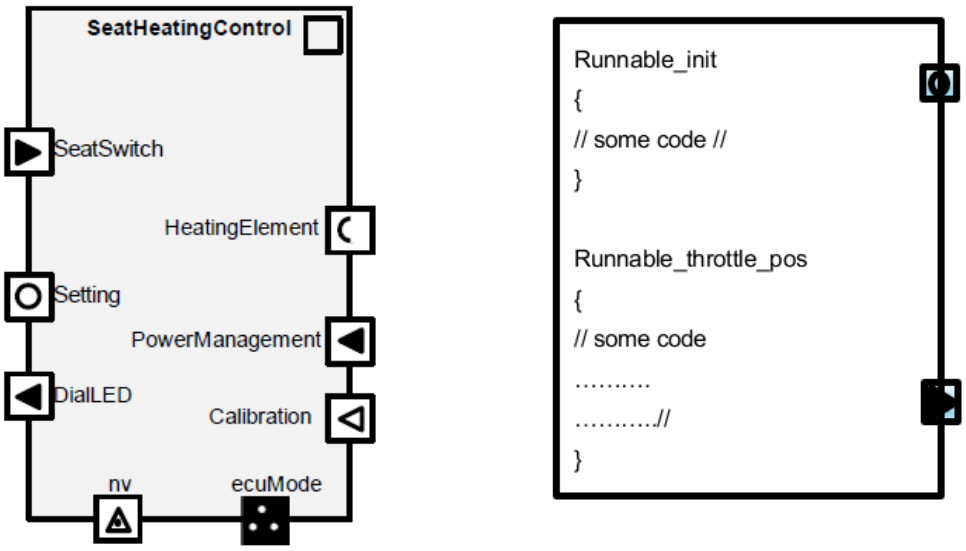


Figure 2.1: AUTOSAR - Layered software architecture [2].

code with one or more function definitions implementing a particular functionality. Those function definitions are also known as runnable entities. According to AUTOSAR standard, a runnable or a runnable entity is also the smallest piece of code schedulable by the RTE [15].

It is to be noted that in a single ECU there can be one or more SWCs. These SWCs execute in close cooperation to realize the function of the whole ECU. The SWCs also communicate with each other in passing variables and parameters. To do so, the AUTOSAR has defined a dedicated set of ports through which the SWCs interact with each other, and in some special cases both with the BSW modules and the RTE. Figure 2.2 represents the general structure of an SWC with various port types and also the internal structure of the SWC with runnable entities.

The Virtual Function Bus (VFB) is another important concept within the AUTOSAR framework, which means the interconnection of Application SWCs via a virtual bus system in the logical system architecture. The VFB concept is a generalization irrespective of the ECU to which the component actually belongs. For example, the inter-ECU and intra-ECU communication distinction are completely abstracted, and only the logical interconnections among the SWCs are visible in the VFB view. This explains why the Application SWCs, within an AUTOSAR environment, do not belong to the specific ECUs, and that the components can be distributed across the ECUs within the vehicle network. Figure 2.3 shows an interconnection of such components in the VFB level.



(a) SWC - Blackbox view

(b) SWC - Whitebox view

Figure 2.2: SWC - General structure [8].

2.1.2 Run Time Environment

The RTE forms the key part of the AUTOSAR system and cements the ASW and the BSW through clearly defined APIs. The Application SWCs do not need to be aware of the internal system behaviour, and the services offered by the BSW modules to the ASW are realized only via the RTE. The functionalities of the RTE layer can be grouped into two areas:

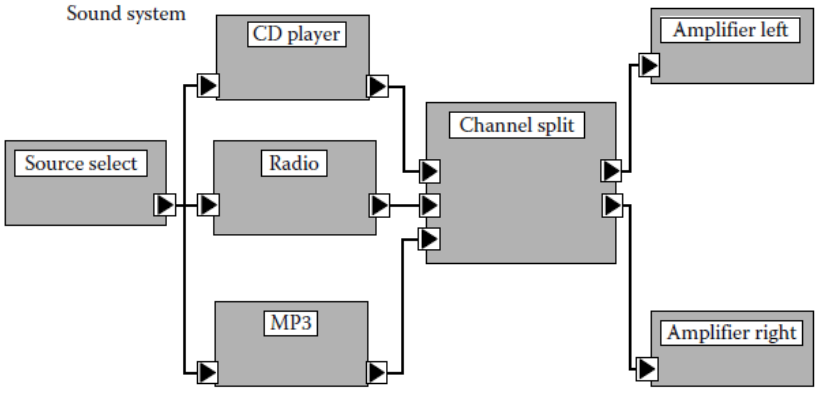


Figure 2.3: SWC interconnection in VFB level [2].

- Realization of communication paradigms among Application SWCs.
- Interfacing the ASW and the BSW.

In order to support the communication between the Application SWCs, the RTE provides an API header, using which the Application SWCs can be coded. The RTE header file consists of function prototypes for realizing the port communication between the SWCs. An example of RTE function prototype is *Rte_send_portA_d()*, where an SWC sends data element *d* via port A [2]. The RTE also checks for "data consistency" during communication [2].

The RTE additionally includes task bodies, which hold the function calls to the runnable entities. These are the dedicated tasks of the OS to which the runnable entities are mapped. The problem of 'which runnable entity belongs to which OS task' is resolved in the RTE configuration phase (Section 3.5.2). The OS tasks also await notifications from RTE events during execution. Further, the scheduling of these OS tasks is handled by the Basic Software Scheduler (BSS), which is the global scheduler in the AUTOSAR environment. The BSS is a part of the OS situated in the BSW [15]. Moreover, the RTE also acts as a medium for the services provided by the BSW modules to the upper layers. AUTOSAR has defined standardized port interfaces (Section 3.3.2) for handling the BSW services to the application layer.

2.1.3 Basic Software

This section describes the BSW portion - the third layer in the AUTOSAR software architecture. The content described in this section is based on [16]. As indicated earlier, the BSW forms the core part of the AUTOSAR system. The BSW can be further subdivided into the following layers: Service Layer, ECU Abstraction Layer, Microcontroller Abstraction Layer (MCAL) and Complex Drivers [16]. The BSW layers are ordered hierarchically from hardware specific drivers to managerial layers and are abstracted from each other via standardized API calls. However, the complex driver is housed as an independent layer. The basic arrangement of these layers within the scope of the BSW can be seen in Figure 2.4.

The software layer written over the microcontroller hardware level is the **Microcontroller Abstraction Layer (MCAL)**. As the name suggests, the MCAL layer is in "direct access" with the microcontroller hardware and abstracts the layer situated above it via standardized interfaces [16]. The MCAL layer provides interfaces for the upper layers to access individual peripherals of the microcontroller. Moreover, this layer also contains drivers such as communication drivers, I/O drivers and memory drivers for microcontroller on-chip peripherals.

The **ECU Abstraction Layer** defines a broader group of hardware peripherals in addition to the microcontroller specific peripherals. It provides interfaces for both microcontroller on-chip peripherals as well as external hardware like a watchdog timer. However, the ECU abstraction layer cannot access the microcontroller directly, but only via the MCAL layer.

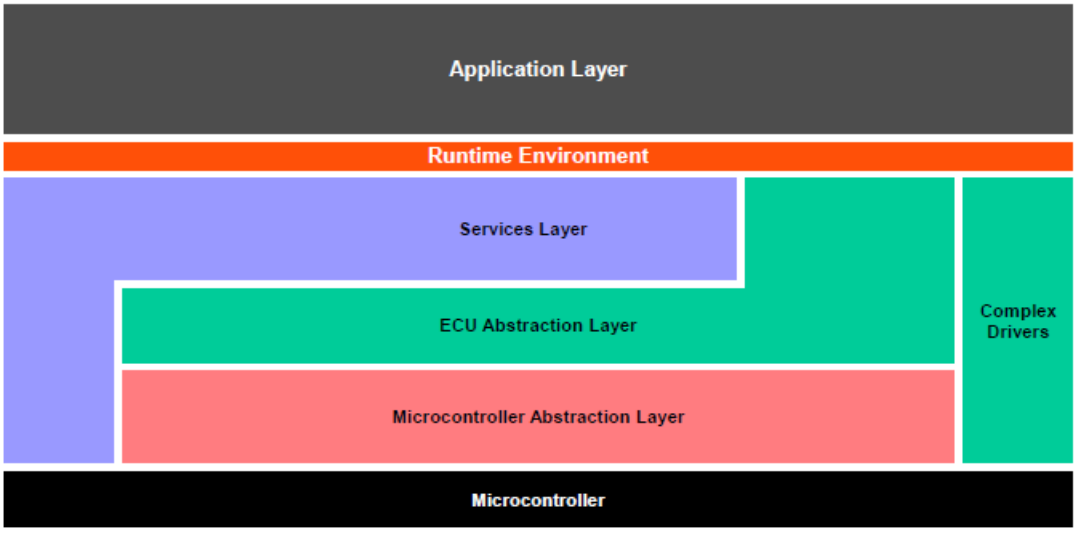


Figure 2.4: BSW layers [16].

The **Complex Drivers** form a separate layer and are situated independently from the hierarchical structure of the BSW layered architecture, although communication may be possible with other BSW modules. This layer is mainly provided for "migration purposes" - to accommodate features that are not AUTOSAR compliant, or to incorporate any "time-critical constraints" into the AUTOSAR environment [16].

The topmost layer in the BSW hierarchy is the **Service Layer**. It is the managerial layer for all the services provided to the RTE and the ASW. Some of the services provided are OS services, memory services, communication services, and mode management, etc. The BSW hierarchical model can be further categorized into various functional groups based on their application scope, as shown in Figure 2.5.

The **System Services** are related to the group of services such as OS, mode management, diagnostics event management, etc. Normally, these services are used by the application layer as well as other BSW modules. The **Memory Services** form the management group for the Non-volatile Random Access Memory (NVRAM) access. The NVRAM manager (NvM) provides necessary services and routines for the ASW for reading and writing non-volatile data into the NVRAM. The **crypto services** are used in the management and access of "cryptographic primitives" [16].

The functional group responsible for the inter-ECU communication by transferring the data via the bus lines is the **Communication (COM) Manager**. In addition, the COM manager acting as Diagnostics Communication Manager (DCM) also handles the communication capabilities with external diagnostic tools. The COM layer has dedicated COM stacks and Protocol Data Unit (PDU)

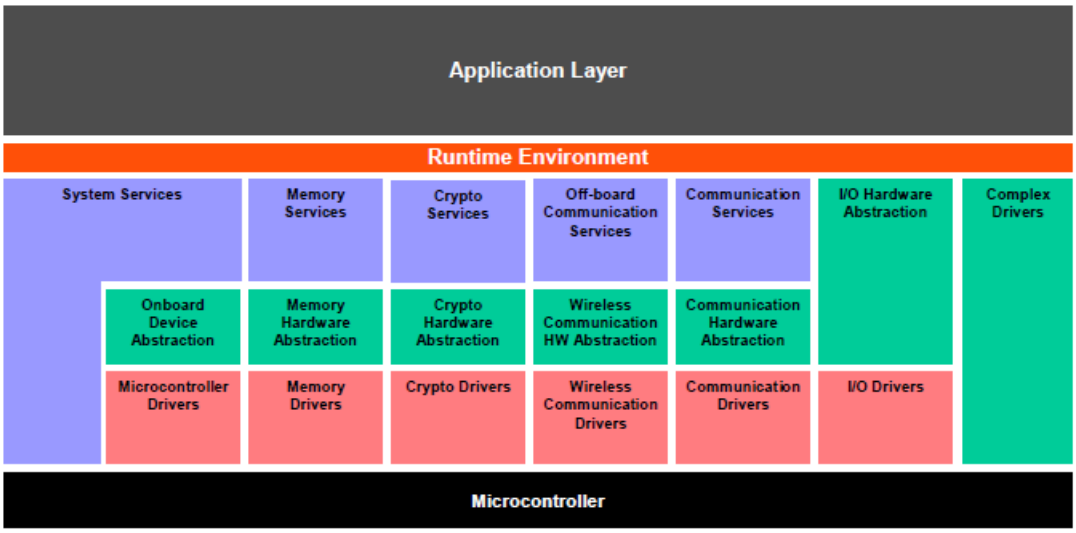


Figure 2.5: BSW functional groups [16].

router, which can seamlessly handle protocols such as Controller Area Network (CAN), Local Interconnect Network (LIN) and FlexRay. Similarly, the **Off-board Communication services** are related to "Vehicle-2-X" communication over wireless medium [16].

The **I/O Hardware Abstraction** is related to the sensor I/O read and write functionalities and is considered a part of VFB despite being a BSW software module. The module communicates with the application layer via port interfaces on one side, and with the MCAL layer on the other side through standardized APIs.

2.1.4 BSW Conformance Classes

This section describes ways of measuring compliance levels towards the AUTOSAR standard and is based on [2]. The Implementation Conformance Classes (ICC) measure the degree of the conformance of various automotive software implementations towards the AUTOSAR standard. These categories have been defined from ICC1 to ICC3 keeping in mind the step by step process of migration from non-AUTOSAR models to AUTOSAR models. The conformance classes, however, are measured only with respect to the RTE and the BSW modules.

ICC1

In the ICC1 category, the RTE functionality can be integrated with the BSW and implemented as a single entity. The BSW part is not required to follow the AUTOSAR conformed implementation. For this reason, the suppliers are free to add their own implementations in the BSW cluster. However, the interfaces between the ASW and the BSW still need to be AUTOSAR conformed, and the

BSW cluster shall offer all the necessary functionalities mentioned in the AUTOSAR specifications [2].

ICC2

In the ICC2 category, the BSW is classified as the "cluster" of modules based on their functionality such as the RTE part, the OS part, and the COM stack, etc. [2]. The BSW modules are also termed as "BSW clusters" [17]. An individual or a set of BSW clusters can be obtained from different suppliers and integrated as a BSW stack [2].

ICC3

The ICC3 category must follow the fullest AUTOSAR conformance. All the interfaces between the ASW and the BSW and the abstraction levels between various BSW layers must comply with AUTOSAR requirements [2]. The BSW is considered as a single-layered entity with the layers abstracted from each other via standardized interfaces. Unlike ICC2, the RTE layer in the ICC3 category is considered an independent layer from the BSW structure.

2.2 AVL Hybrid Control Unit Software Architecture Overview

This section provides an overview of the software architecture of the AVL Hybrid Control Unit (HCU). It is the AVL proprietary software that will be subjected to AUTOSAR conversion. The content described in this section is based on [18].

The software architecture of HCU constitutes three basic layers: Application Software (ASW), Customer Interface Layer (CIL), and the Basic Software (BSW) part. In spite of being designed based on AUTOSAR principles, the software deviates in major proportion from the AUTOSAR standards in terms of interface handling and development methodology. Figure 2.6 shows an overview of the HCU software architecture. A brief background on choosing the above-mentioned software architecture by AVL is provided in Section 2.2.1 and a description of each specific layer is shown in the subsequent sections.

2.2.1 Background

This section provides a brief background on the software architecture (Figure 2.6) followed by AVL. The AVL HCU software development team started out as an ASW development team for customer projects. The ASW structure follows the design aspects mentioned in Section 2.2.2. At a later point in time, AVL migrated to full-scale ECU software development. The BSW implementations for AVL projects were ordered from Tier 1 suppliers and had to be integrated with the ASW. As a result, the CIL layer was defined by AVL as a means to manage the interfaces between ASW and BSW. In addition, the customer projects being handled[1] by AVL have been non-AUTOSAR

[1]The migration to AUTOSAR methodology had been planned only at the time when this thesis was written.

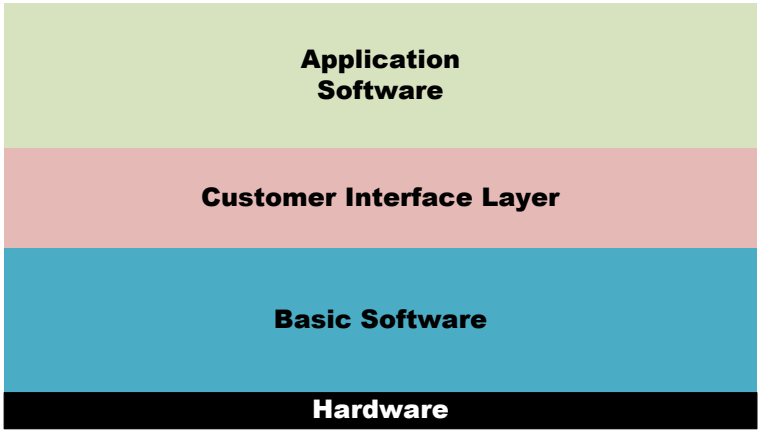


Figure 2.6: HCU software architecture. Adapted from [18].

projects. Therefore, AVL follows their own software development methodology which includes procurement of BSW from suppliers, development of ASW and CIL, and software integration of BSW and ASW.

2.2.2 Application Software

The ASW structure of the HCU software has been developed by AVL. Similar to the ASW in AUTOSAR layered architecture described in Section 2.1.1, the ASW structure in the AVL proprietary software constitutes individual SWCs making up for the software behaviour. The ASW behaviour is also coded in the form of runnable entities. The SWCs in the AVL HCU software are also distinctly grouped into various functional groups based on their functionality.

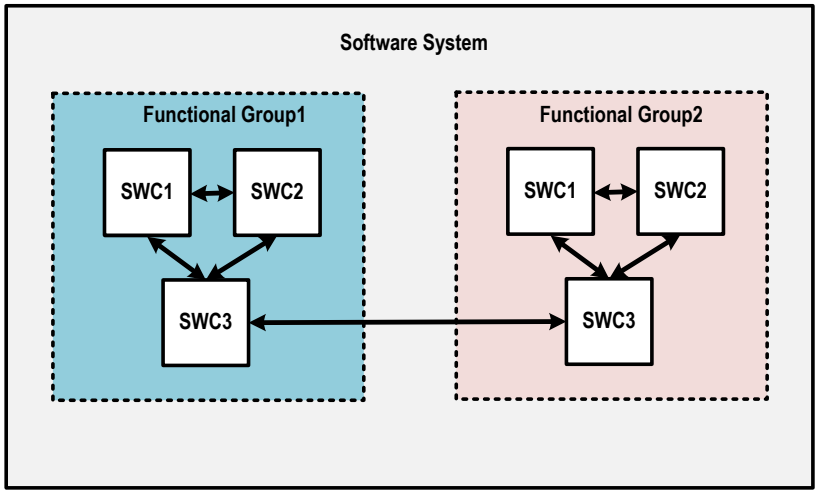


Figure 2.7: AVL HCU software - ASW structure.

Figure 2.7 provides an understanding of the classification of SWCs in AVL HCU software based on their associated functional groups. The set of all the SWCs in the ASW along with the functional groups constitutes the complete software system of the HCU. In contrast to AUTOSAR, where RTE function calls are used for ASW communication, the communication among the SWCs is handled via static global variables. In the ASW code level, this property is directly adopted when a non-AUTOSAR type code is generated from MATLAB/Simulink models. The reader can refer to Section 3.4.1 for more details on the AVL software code generation.

2.2.3 Customer Interface Layer

AVL defines the Customer Interface layer (CIL) as the interfacing layer between ASW and BSW providing a bidirectional signal interface. The CIL layer has been designed to handle all possible interfaces between ASW and BSW. The role of the CIL layer can be understood from Figure 2.8. The HCU Software architecture document [18] mentions the following functionalities to be offered at the CIL level:

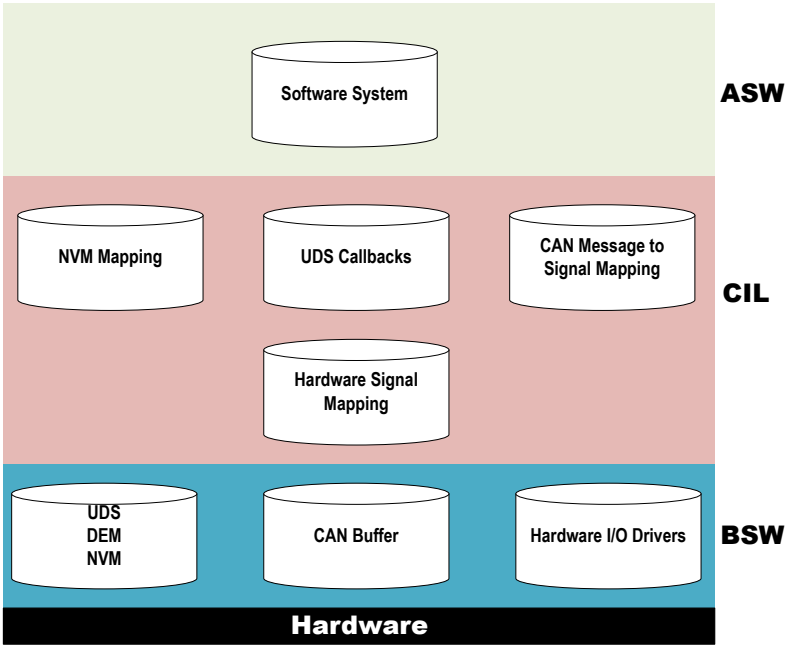


Figure 2.8: Role of layers in HCU software architecture. Adapted from [18].

- Providing signal interfaces to the ECU I/O signals.
- Interfacing signals to be transmitted over CAN bus lines. Additionally performing CAN signal validity checks, etc.
- Interfacing diagnostic event signals.

- Providing interfaces for the variables to be loaded into NVRAM.
- Invoking the ASW runnable entities with OS task execution.

2.2.4 Basic Software

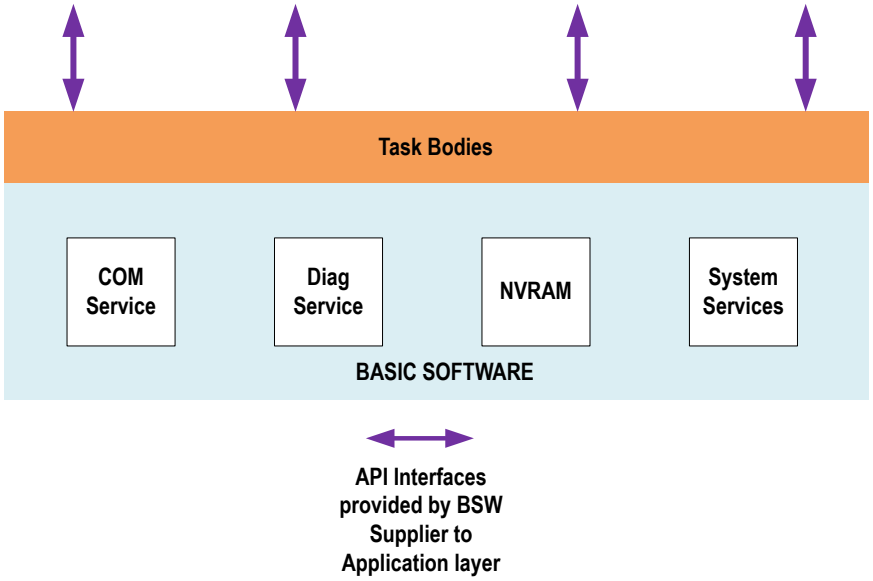


Figure 2.9: BSW structure - AVL HCU software.

The BSW portion of AVL HCU software is procured from the supplier along with the hardware. A schematic of the BSW is shown in Figure 2.9. The 'sky-blue' portion indicates the core part of the BSW, which provides the class of functionalities related to the OS, communication and diagnostic services, memory services and other software drivers, etc. [19]. The implementation of the BSW is proprietary to the supplier. The supplier additionally defines APIs (marked 'purple' in Figure 2.9) and task bodies for providing the BSW services to the upper layers. The API interfaces are used to exchange information such as the CAN signals, diagnostic callbacks, I/O and NVRAM signals, etc., between the BSW and the ASW. The task bodies are used to invoke the ASW runnable entities.

The exact software architecture used in the BSW implementation is not clearly known as it is not indicated by the supplier in the BSW documentation, and additionally the BSW is delivered to AVL as compiled object files. Hence it has been assumed that the BSW implementation is supplier proprietary and are not necessarily based on AUTOSAR BSW specifications. Additionally, the API interfaces to the upper layers are also supplier-specific (defined with respect to the CIL layer) and are not based on AUTOSAR specifications. Hence the BSW, as a whole entity, cannot be inferred to be AUTOSAR compliant.

3. AUTOSAR Compliance Deviation Analysis

In order to convert the AVL HCU software towards AUTOSAR compliance, it is important to understand the deviations from the AUTOSAR standard. The V-Model type of SDLC has been chosen, since it is a clear representation of the software development process and is also widespread in usage across the industries. The deviations from AUTOSAR have been studied across the V-Model process flow and presented in this chapter.

3.1 Deviation Analysis along V-Model Phases

Like Waterfall and Spiral Model, V-Model is a type of SDLC representing the sequential steps involved in the software development process [20]. The V-Model flow of software development aims at seamless and fine-grained control of the development and testing process. As the case with software development in other areas, the V-Model process flow methodology is also widespread in usage in automotive software development. The methodology describes a "series of process stages" from requirements, high-level design to low-level implementation in the design phase (left trunk of V-diagram), and from unit testing until acceptance testing in the validation phase (right trunk of V-diagram) [21], as shown in Figure 3.1.

While applying the V-Model methodology in the case of automotive software development, the work stages across the design and the validation phases are appropriately shared among the OEMs, Tier 1, supplier companies and service providers. The software development life-cycle starts with the requirements phase. The system and component requirements based on customer expectations and other boundary conditions are prepared by the OEMs in this phase and are quoted to various supplier companies.

The design and implementation phase usually takes place at the supplier side of the particular component (e.g. ECUs). The high-level design involves the design of architectural concepts of the particular software. The low-level design refers to the design of granular concepts such as models,

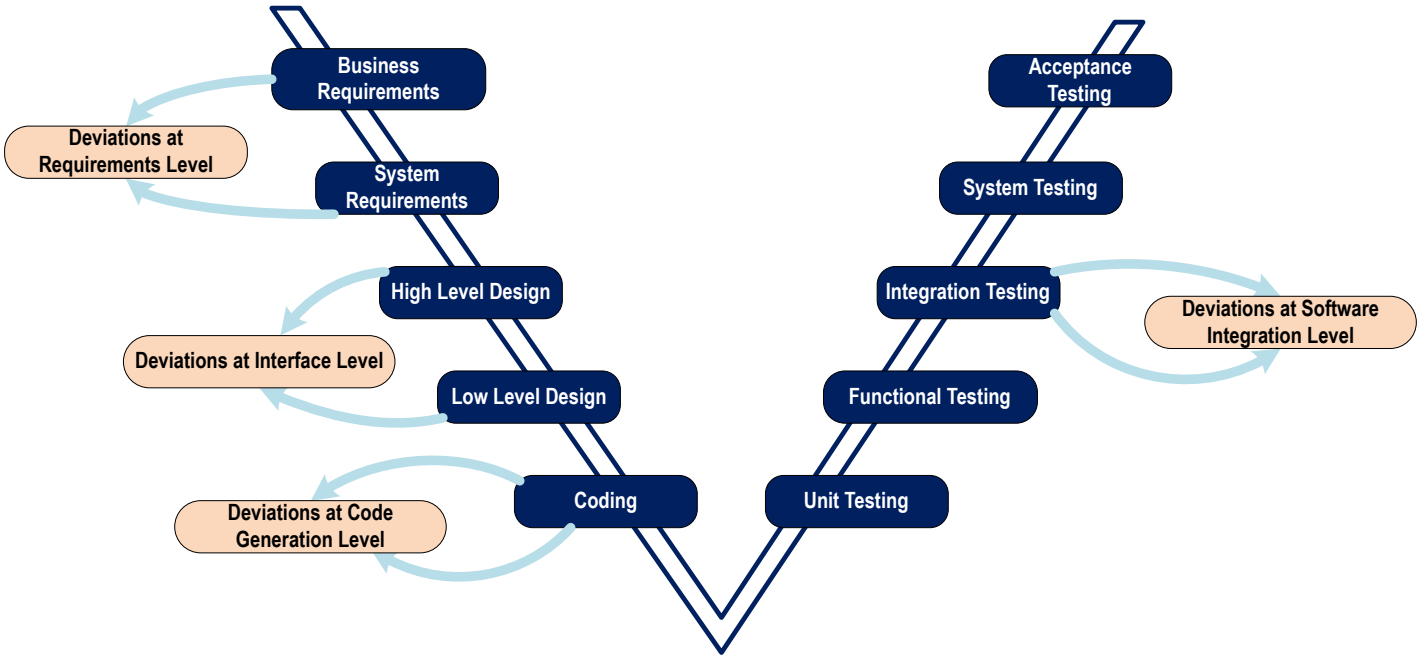


Figure 3.1: Deviation analysis across V-Model. Adapted from [22].

interfaces and the implementation logic, etc. [21]. After the implementation phase, the testing is performed at integration, component and system level. The integration and component-level testing are the responsibility of the supplier companies, while OEMs handle the system-level testing. The V-Model also follows the back and forth style of modelling, wherein any modifications bound to happen at any level in the design or validation workflow shall be reflected in all the preceding levels.

While observing the deviations of AVL HCU software from the AUTOSAR standard, it is evident that the analysis should be carried out at all levels of the SDLC. The software deviation analysis was therefore studied under the following categories, as shown in Figure 3.1:

- Deviations at requirements level.
- Deviations at architecture and interface level.
- Deviations at model development and code generation level.
- Deviations at software integration level.

The following sections provide a detailed account of the categories of deviation analysis mentioned above.

3.2 Deviations at Requirements Level

AVL[1] uses the requirement specifications in order to quote the supplier about the BSW and hardware requirements. The deviations inferred in the requirements level can be shown in the below categories. The descriptions in the below sections are based on AVL's BSW requirement document [19].

3.2.1 BSW Architecture Requirements

AVL Requirements	AUTOSAR Requirements
AVL does not specify a particular software architecture for the BSW in their requirements to the supplier. This entails that the BSW supplier has the freedom to use their proprietary software architecture and implementations as long as all the essential BSW functionalities are met [19].	The BSW requirements must strictly follow AUTOSAR specifications. AUTOSAR specifies a well-defined software architecture for the BSW [16]. All the hierarchical arrangement of the BSW modules and all the abstraction levels in the BSW layers must be implemented as specified in the AUTOSAR specifications.

Table 3.1: Deviations in BSW requirements architecture-wise.

3.2.2 BSW Interface Requirements

AVL Requirements	AUTOSAR Requirements
AVL BSW requirement states that API interfaces shall be provided by the supplier for the access of BSW signals by ASW (through CIL) [19]. However, AVL does not specify a specific format [a] for these API interfaces. This means that the BSW supplier can choose their own format for the API interfaces from BSW, and the format need not be AUTOSAR specific.	In AUTOSAR case, all the interfaces from the BSW to upper layers (through RTE) are standardized. AUTOSAR defines a specific format for these API interfaces. The supplier implementation of the API interfaces must conform with the AUTOSAR standard.

[a] The 'format' in this case refers to the name and syntax of the API interfaces from BSW.

Table 3.2: Deviations in BSW requirements interface-wise.

[1] The AVL Powertrain Controls Dept.

3.3 Architectural and Interface Level Deviations

3.3.1 Interface Handling in AVL HCU Software

This section describes the interface handling in AVL HCU software. The AVL HCU software architecture has been designed by AVL and is architecturally comparable to the AUTOSAR architecture shown in Figure 2.1. Nevertheless, there are inherent differences in the low-level design aspects such as interface handling. Figure 3.2 shows an illustration of the interface handling in AVL HCU software. As indicated in Section 2.2.4, the supplier provides the BSW along with the API interfaces to the upper layers and the task bodies.

The CIL layer is implemented by AVL. The API interfaces (marked 'purple' in Figure 3.2) provided by the supplier are used to integrate the CIL layer with the BSW. The task bodies are also filled with function calls to the ASW runnable entities at the CIL layer level. Alternatively, it can also be understood that the CIL is not a standardized layer; and CIL has been defined by AVL to manage the interfaces provided by the BSW to the application layer. In short, all the interfaces from ASW to BSW are handled only via the CIL layer. Additionally, any manually implementable functionalities such as CAN CRC check, and hardware fault detection, etc., are also implemented at the CIL layer level.

At the ASW level, communication among the SWCs involves static global variables (marked 'red' in Figure 3.2). The diagnostic, NVRAM and mode information interfaces are routed only through the CIL layer via variable mapping or function calls (marked 'blue' in Figure 3.2).

3.3.2 Interface Handling in AUTOSAR Standard

This section provides details on the interface handling in AUTOSAR software models. An illustration of types of interfaces used in the AUTOSAR standard is shown in Figure 3.3.

The interfaces have been classified into three types based on their scope of application within the layers. The **standardized interfaces** (Figure 3.3) are defined by the AUTOSAR standard. These interfaces are standardized C-APIs and are used only by the BSW modules while communicating with each other [16]. The **AUTOSAR interfaces**, on the other hand, define port communication between the Application SWCs [16]. These interfaces are not standardized by AUTOSAR, and the naming conventions are based on the name of the port variables. The third category of interfaces, the **standardized AUTOSAR interfaces**, refer to the standardized API calls provided by the service layer to the Application SWCs, for example, the diagnostic services offered by the Diagnostic Event Manager (DEM) to the application layer [16, 23].

Additionally, AUTOSAR defines port types and port interfaces for different communication types involved among the SWCs. In the high level, the port types can be classified into 'Pport' and 'Rport' [8]. The **Pport** is the provider of the data, and the **Rport** is the receiver or requester of the

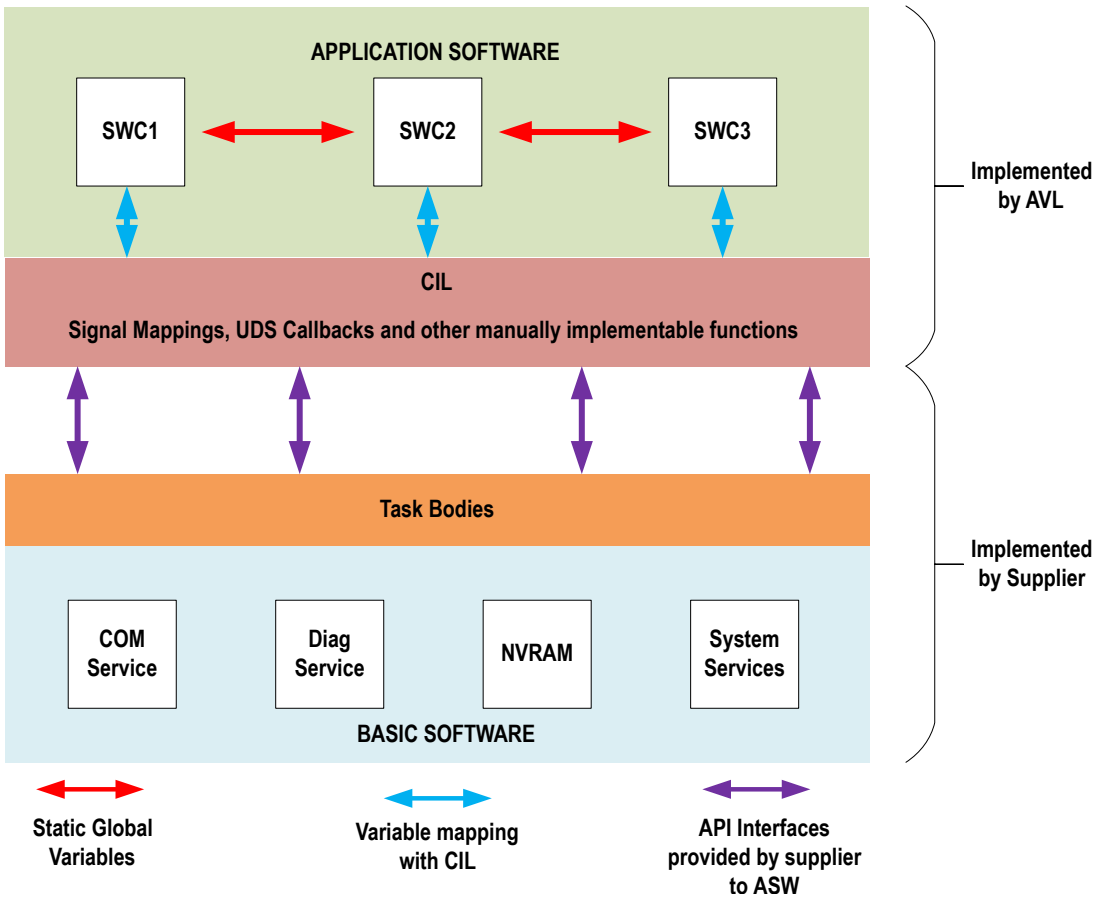


Figure 3.2: Interface handling in AVL HCU software.

data. Moreover, the port types are generally available for various categories of port interfaces, as shown in Figure 3.4. According to [8], the various available port interface categories are:

- **Sender-Receiver** is the type of interface defined especially for data communication, wherein the sender port transmits the data to the receiver port.
- **Client-Server** interface is for client-server operation. The client requests the server for an operation to be performed via function calls, and the server responds with the results of the operation.
- **Non-Volatile (NV)** interface is used for the communication between NvM and the application in order to read and write data from and into the non-volatile memory.
- **Mode Switch** interface plays a role in signalling the mode transfer from mode managers to the mode users. The mode users are SWC instances, which are generally the requester of mode change, and a mode manager SWC initiates switching of modes.

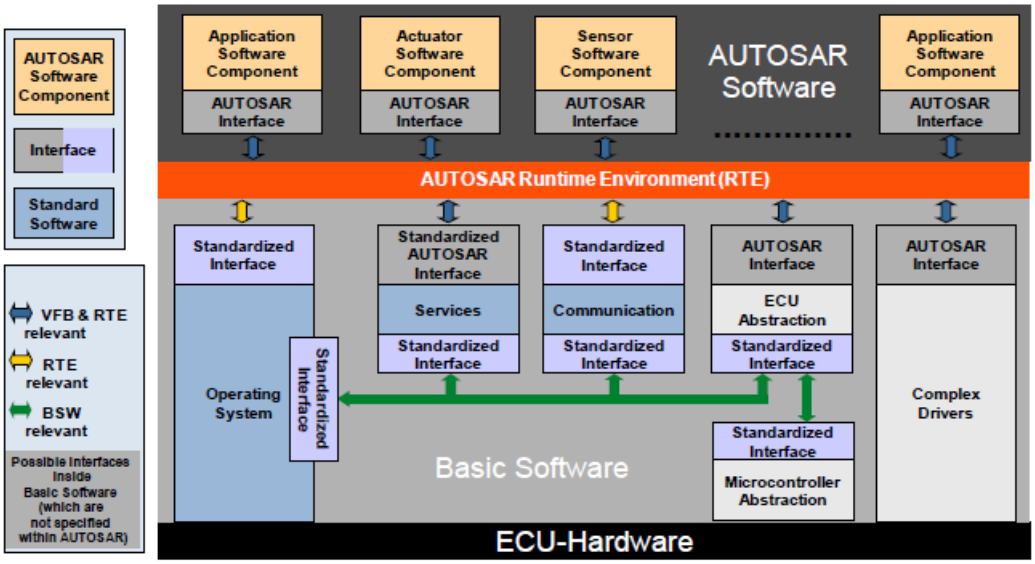


Figure 3.3: Interface handling in AUTOSAR layered software [8].

More details on various port types and the related interfaces can be found in [8]. The AUTOSAR standard also prescribes various types of SWCs that can use the above-mentioned port types and the related port interfaces. An illustration of SWC has already been shown in Section 2.1.1. The description of different SWC types are as follows [8]:

(A) The **Application Software Component** is used to code the application runnable entities which communicate through ports. In general, all the port types mentioned above are used by the Application SWC, so that it communicates with all kinds of SWCs such as NvM, mode managers, etc. However, an Application SWC can access sensor signals and I/O signals only via a Sensor and Actuator SWC type interfaced with ECU Abstraction layer [8].

(B) The **ECU Abstraction Software Component**, also known as I/O Hardware Abstraction Software Component, is used to access the I/O and sensor signal data and pass to the application layer. This type of SWC is situated in the BSW and communicates with the MCAL Layer on one side through standardized C-APIs in order to retrieve the input signals, and interfaces with the Sensor SWC in the application layer on the other side via client-server interface [24]. Therefore, the ECU Abstraction SWC is provided with a mandatory Pport (server). Although situated in the BSW, the I/O Hardware Abstraction forms a part of the VFB because of the presence of AUTOSAR interfaces.

(C) The **Sensor-Actuator Software Component** is also located in the application layer. This type of SWC includes sensor and actuator related application functionalities and acquires the services of ECU Abstraction layer to access the sensor and I/O signals from the hardware [8].

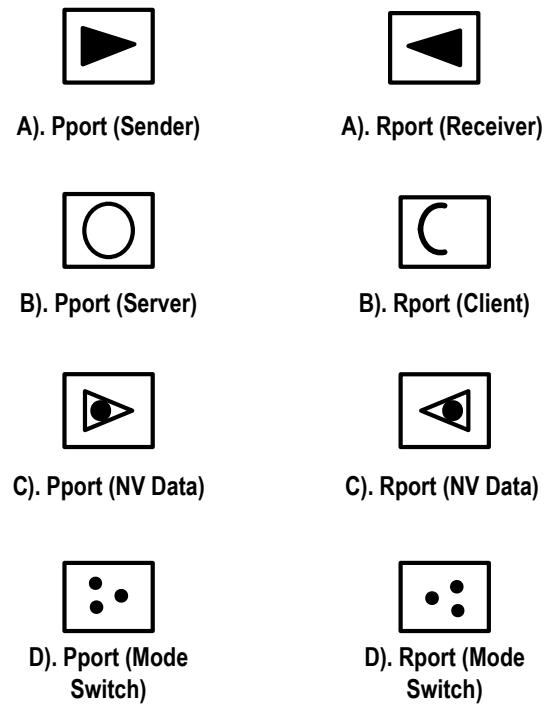


Figure 3.4: Common port types used in AUTOSAR for communication between SWCs. Adapted from [8].

Therefore, these SWCs are normally instantiated with a mandatory Rport (client) for the I/O interaction.

(D) The **Service Software Component** is used to provide BSW services to the upper layers, for example, DEM services to the Application SWCs. Hence, this type of SWC is instantiated in the BSW and communication with other BSW modules is also possible [8]. The Service SWC type is usually associated with standardized AUTOSAR interfaces, which are standardized client-server ports. Some of the use cases of Service SWC instances can occur as mode managers, diagnostic service providers or NvM managers, etc.

(E) The **NV Block Software Component** represents the NvM of the BSW and is normally instantiated in the RTE layer. This type of SWC uses NV interfaces for NV data transfer and client-server interfaces in order to provide the related NvM services to Application SWCs [8].

(F) The **Service Proxy Software Component** is a special type of SWC to transfer mode information from one ECU to another. While an Application SWC is not allowed to request mode related services from a mode manager located in another ECU, the Service Proxy SWC type serves as a proxy to take the mode related communication across ECU boundaries [25].

(G) The **Parameter Software Component** is used as a container for all the global calibration parameters. The Parameter SWC uses parameter interfaces (a type of Sender port) to share these calibration parameters across Application SWCs [8].

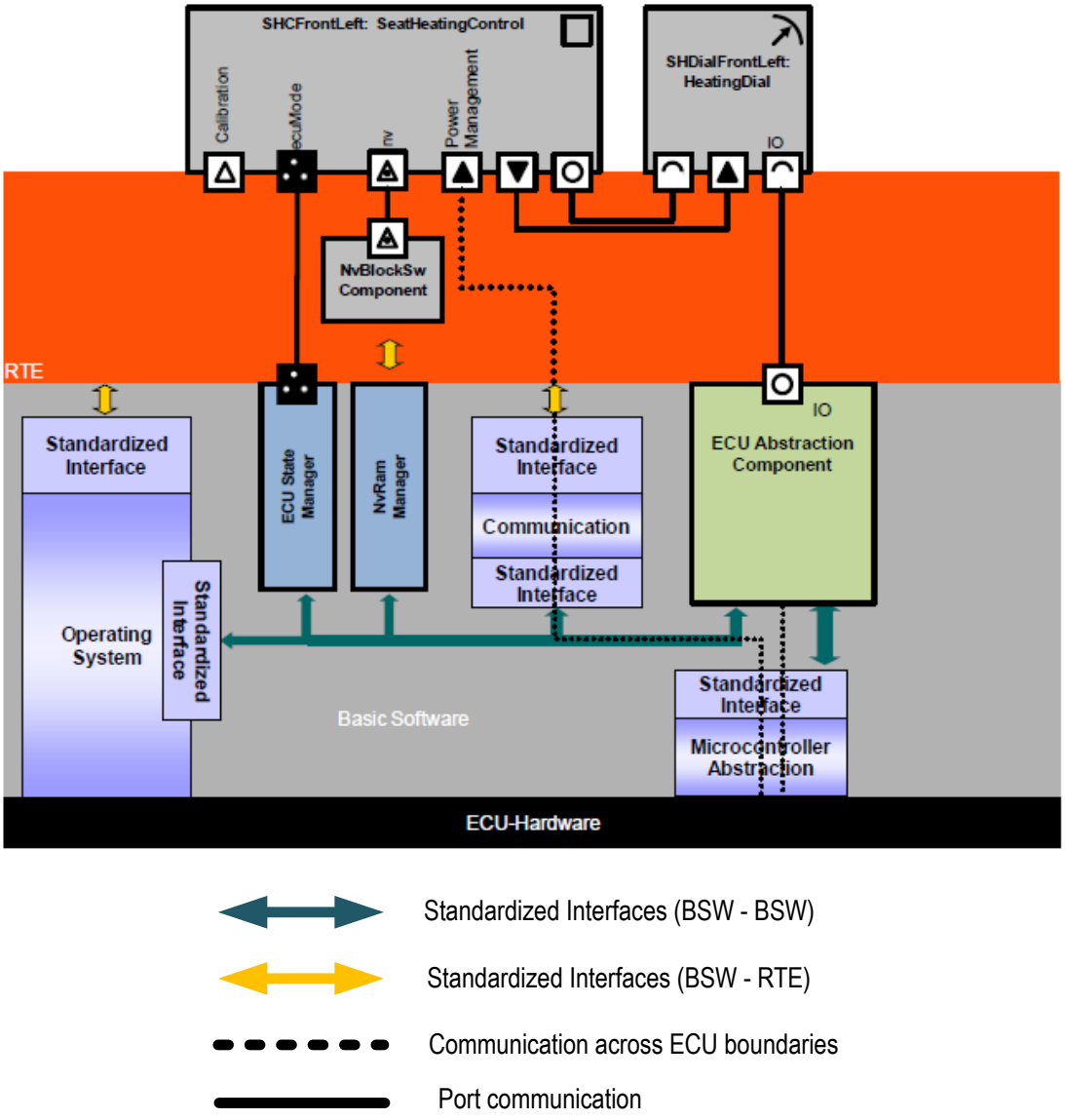


Figure 3.5: An illustration of interface handling in AUTOSAR environment using port types and SWC types. Adapted from [8].

An illustration of interface handling using different SWC types and port types is shown in Figure 3.5. This example shows an ECU software module with two SWC instances present in the application layer: *SeatHeatingControl*, an Application SWC, and *HeatingDial*, a Sensor SWC type. Both the SWCs communicate with each other and also with other BSW modules through various port interfaces. All the communication mechanisms are handled via the RTE ('red' portion in Figure 3.5). It can be seen that the communication between the SWCs in the application layer involves either sender-receiver or client-server ports. The communication with the BSW, on the other hand, involves interface categories such as the NV data transfer, COM interface, mode transfer, and I/O data access, etc. The mode-switch ports are used to transfer the mode information from ECU state manager in BSW to Application SWC *SeatHeatingControl*. In the case of non-volatile (NV) data handling, an NV Block type SWC is configured in the RTE, which represents the NvM and uses NV ports and standardized services from NvM to read and store the NV signals into NVRAM [26]. Besides, the COM stack is responsible for handling the inter-ECU communication mechanism involving external bus lines (e.g. CAN). In the use case shown in Figure 3.5, the information related to the power management interface (this information is received externally) is read by the COM stack and mapped to the receiver port of *SeatHeatingControl* at the RTE level. The ECU Abstraction SWC type interfaced with the Sensor component *HeatingDial* is used for accessing the I/O and sensor signals. As indicated earlier, the ECU Abstraction SWC type, in the use case shown in Figure 3.5, acts as a server and provides services related to I/O signals read/write to the Sensor Component using a server port. The port type indicated in the leftmost corner of *SeatHeatingControl* is the calibration interface. The use case of this type of interface includes the calibration parameter access from an external Parameter SWC type, wherein all the global calibration parameters are written. Apart from the interface categories discussed above, it can also be noted that the BSW modules beneath the RTE use only standardized APIs for communication among them and also with the RTE (shown 'blue' and 'yellow' in Figure 3.5).

3.3.3 Differences in Scheduling Concepts

This section compares the scheduling approaches for runnable entities followed in the AVL HCU software and the AUTOSAR standard. The scheduling concepts used in both the software models are almost similar in approach: the task bodies are used to invoke the runnable entities. In AVL HCU software, the task bodies are provided by the BSW supplier as mentioned in Section 2.2.4, wherein the function calls to the runnable entities are included by AVL. In the AUTOSAR standard, the mapping of the task bodies to runnable entities is determined in the RTE configuration phase (Section 3.5.2) [15]. It is important to introduce the task types: *basic* and *extended* before we discuss further on the scheduling concepts. A basic task does not terminate by itself due to a waiting state. An extended task has OS events associated with it and it has wait points that require the occurrence of the associated events to proceed with the task execution [27]. The discussion in this section is limited to the relationship between the OS tasks and runnable entities and does not cover in detail the scheduling concepts involved at the OS level.

In the case of AVL HCU software, the BSW supplier provides a total of four task bodies, which are also basic tasks with different periodicities (1ms, 5ms, 10ms, and 100ms, etc.), for scheduling

the runnable entities. The scheduling algorithm used by the BSW supplier for these tasks and the pre-configured priorities are not visibly known since these are supplier-specific implementation in the BSW object files delivered to AVL. Among the tasks mentioned above, only the 10ms task has been used by AVL to invoke the ASW runnable entities. An illustration of a task body with runnable entities is shown in Figure 3.6. For illustrative purposes, the task name has been chosen as *T1* and the runnable entities have been named from *Runnable_1* to *Runnable_n*. It can be seen from Figure 3.6 that the runnable entities (*Runnable_1* to *Runnable_n*) are invoked sequentially as the *T1* is scheduled for every 10ms. The complete execution of task *T1* along with the runnable entities occurs well within the next arrival time of *T1*. A possible reason for AVL to use the 10ms task is to align the task runtime with the cycle-time of CAN message, which is 10ms for all the HCU messages. Besides, the order of invocation of the runnable entities is determined by the execution order generated by the HCU software system model via the Model-in-the-Loop (MIL) simulation. Furthermore, it can be seen from Figure 3.6 that no events, alarms or extended task types are used in the scheduling concept of AVL HCU software. Since the runnable entities are executed sequentially one after another, there is no synchronized execution among the runnable entities.

Referring to Figure 3.7, in the AUTOSAR standard, there is a provision to use more than one task type (basic or extended) depending on the application context. The AUTOSAR standard defines RTE events, which are also the means to trigger the execution of runnable entities [15]. In addition, the runnable entities can be classified into category 1, in which the runnable has no wait points, and category 2, in which the runnable has one or more wait points. These wait points are resolved by the

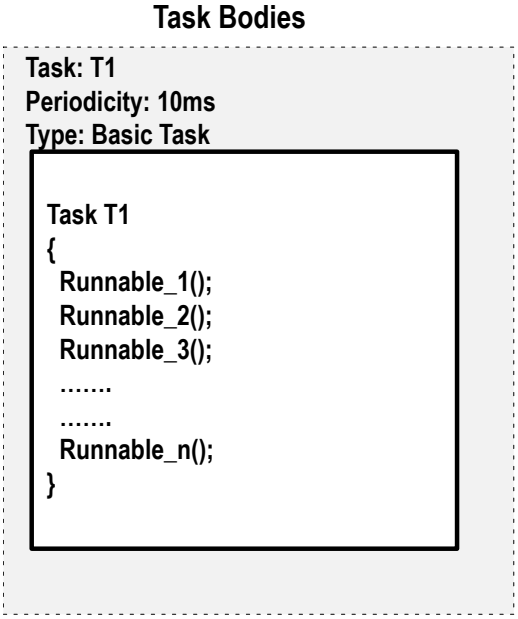


Figure 3.6: An example of a task body used to invoke ASW runnable entities in AVL HCU software.

occurrence of a typical RTE event (e.g. *DataReceivedEvent* [15]). The mapping of runnable entities to the task types is performed in the RTE configuration and the mapping information is recorded in the ECU Configuration Description. According to [15], the OS task to runnable mapping depends on certain criteria: A basic task is used for category 1 runnable entity with no wait points, and an extended task is used when the runnable entity is of category 2 and has one or more wait points. Based on the task mapping information in the ECU Configuration Description, the task bodies are generated during RTE generation.

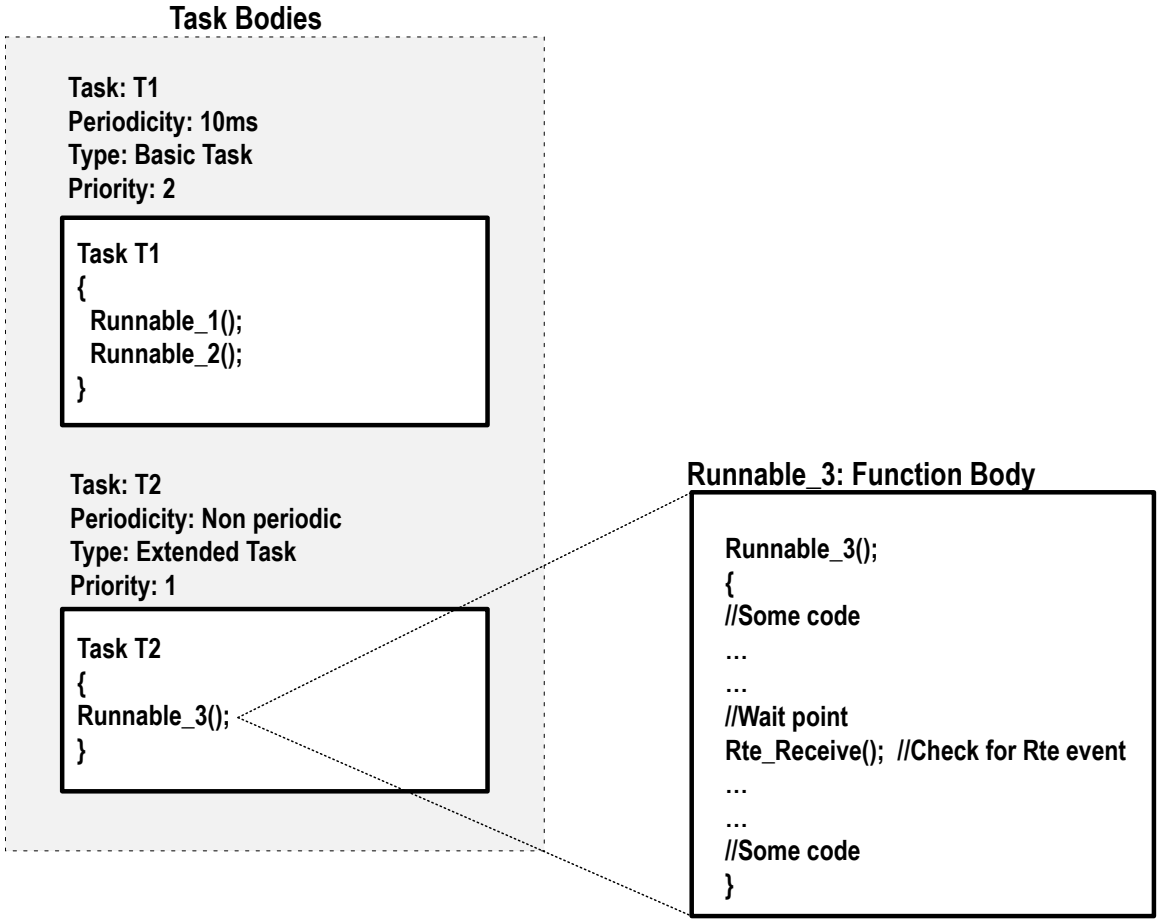


Figure 3.7: An example of a runnable entity to task body mapping done in AUTOSAR methodology. Adapted from [15].

In the example shown in Figure 3.7, a basic task *T1* and an extended task *T2* have been used. The runnable entities *Runnable_1* and *Runnable_2* are periodic runnables of category 1 (for example, let us assume the cycle-time is 10ms) and the runnable *Runnable_3* is of category 2 which has a wait point for an RTE event *DataRecieveEvent*. It can be seen that the runnable entities *Runnable_1*

and *Runnable_2* are mapped to task *T1* in the RTE configuration phase. The sequence of execution for these runnable entities is also specified beforehand in the configuration phase and is available in the ECU Configuration Description. Additionally, the *Runnable_3* is mapped to the extended task *T2*. In can also be seen that, in the function body of *Runnable_3*, the wait point for checking the occurrence of RTE event *DataRecieveEvent* is implemented using the RTE API *Rte_Receive()* [15]. The priorities of the tasks to which the runnable entities are mapped are also decided during the OS configuration phase [27]. In the example shown in Figure 3.7, the priorities have been assumed '1' for task *T2* and '2' for task *T1*.

3.4 Deviation at Model Development and Code Generation Level

This section compares the model development aspects of AVL's methodology and AUTOSAR methodology.

3.4.1 Model Development Aspects in AVL HCU Software

In this section, the model development process of AVL HCU software and the related software tools used are explained. As shown in Figure 3.8, the software development process begins with the definition of the system requirements. The system in this context refers to the system of all the powertrain ECUs[2] developed by AVL. From the system requirements, the subset of requirements related to the HCU module is filtered out and the ECU architecture is designed. The ECU design step focuses on the definition of all the SWCs within the HCU software system and ECU labels such as the I/O signals, calibration, and measurement variables and system constants, etc. The calibration variables, in this case, can also include single parameters, axes (1D arrays) and maps (2D arrays). The **Automotive Data Dictionary (ADD)** [28] tool is used to manage all the ECU labels. The ADD project is created as a separate container stored as *.ddx* files for each SWC model and the I/O and calibration parameters to be used in the model are defined. The *.ddx* is the file format of an ADD database containing the ECU labels of a particular SWC model [28]. The ADD is also integrated with the Maestra environment in the back-end[3] and is responsible for keeping the **.ddx* file up-to-date with the variable modifications.

The SWC design phase (from Figure 3.8) involves modelling the Application SWCs and generating the ASW code from SWC models using code-generators. The SWC models are developed using a dedicated model-based development tool (e.g. MATLAB/Simulink, dSpace TargetLink, etc.). In the case of AVL HCU software, the SWC models are developed using TargetLink 3.5 integrated with MATLAB version 2013b. An AVL proprietary tool called **Maestra** is also used alongside, which finds application in MIL simulation and testing. The tool provides complete features to set

[2] AVL currently develops Transmission Control Unit (TCU), Hybrid Control Unit (HCU) and Engine Control Unit (ECU).

[3] The 'back-end' in this context refers to the scenario in which the user can work with an integrated environment of software tools, but does not explicitly see how these tools are integrated.

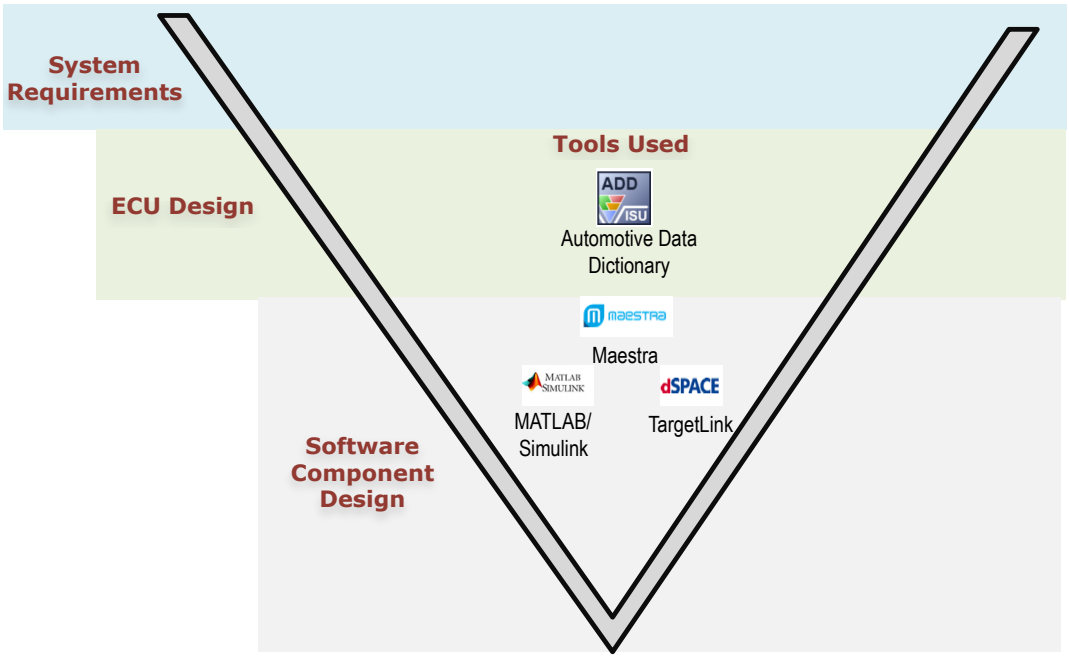


Figure 3.8: Software development workflow - AVL HCU software.

up a MIL simulation environment for the models including generation of test cases for MIL testing. The Maestra framework is integrated into the back-end with MATLAB and TargetLink. The model under test is housed within this Maestra framework.

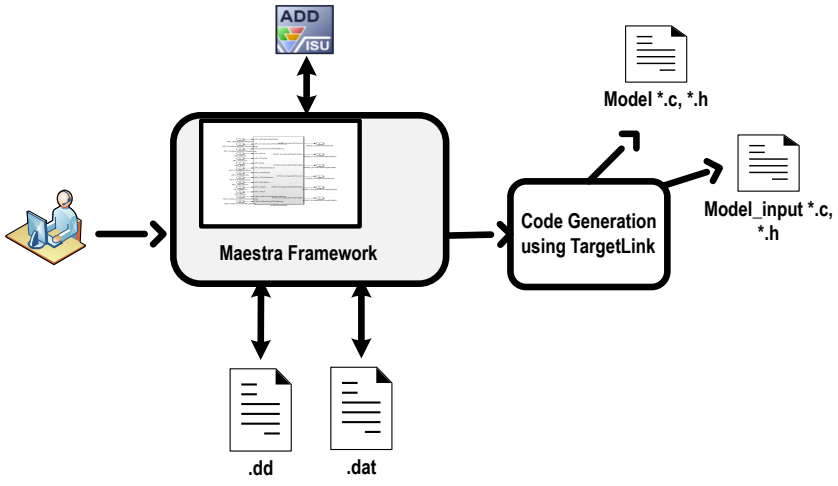


Figure 3.9: Process-flow - AVL HCU software modelling.

The AVL HCU software modelling process (Figure 3.9) involves the development of models in an integrated environment of Maestra framework, ADD, MATLAB, and TargetLink. The model data files specific to the MATLAB and TargetLink environment for denoting the signals and parameters used in the SWC models are managed within the Maestra framework. As indicated earlier, these data files are maintained up-to-date with modifications in the ADD database, for example, a newly added parameter in the ADD database is automatically reflected in these data files. Besides, the TargetLink is used to generate SWC code files.

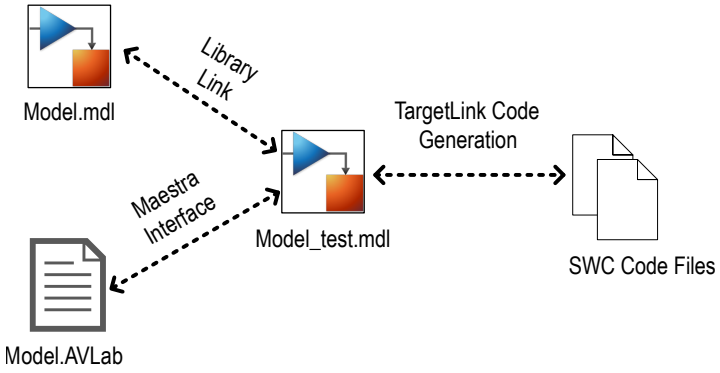


Figure 3.10: Folder structure of the model and generated code in the AVL HCU software.

A fully developed SWC contains the following file entities: a model library, a test model, a Maestra session file and generated SWC code files. The relationship between these file entities is shown in Figure 3.10. The model algorithm is implemented using TargetLink blocks and is stored as a Simulink model library in *.mdl* format (e.g. *Model.mdl*). An additional test model (e.g. *Model_test.mdl*) file is created, which includes the interfaces to Maestra framework and links with the model library mentioned above. This test model can be subjected to MIL testing. Additionally, the *Model.AVLab*, which is also known as the Maestra session file, represents the MIL simulation environment of the model. By loading the session file in Maestra, the test model can be housed within the MIL simulation environment.

3.4.2 Model Development Aspects in AUTOSAR Software Model

The software models in AUTOSAR environment involve port types and SWC types as mentioned in Section 3.3.2. A model development tool supporting AUTOSAR configuration provides the required AUTOSAR template with the necessary port interfaces, wherein the model algorithm can be implemented. Additionally, the tool also provides the necessary platform to configure the settings of ports, runnable entities and RTE events. In the generated source code, the implemented model algorithm is coded as runnable entities.

Another important feature in the AUTOSAR model development is the involvement of the AUTOSAR Extensible Markup Language (ARXML) description files in every phase of development.

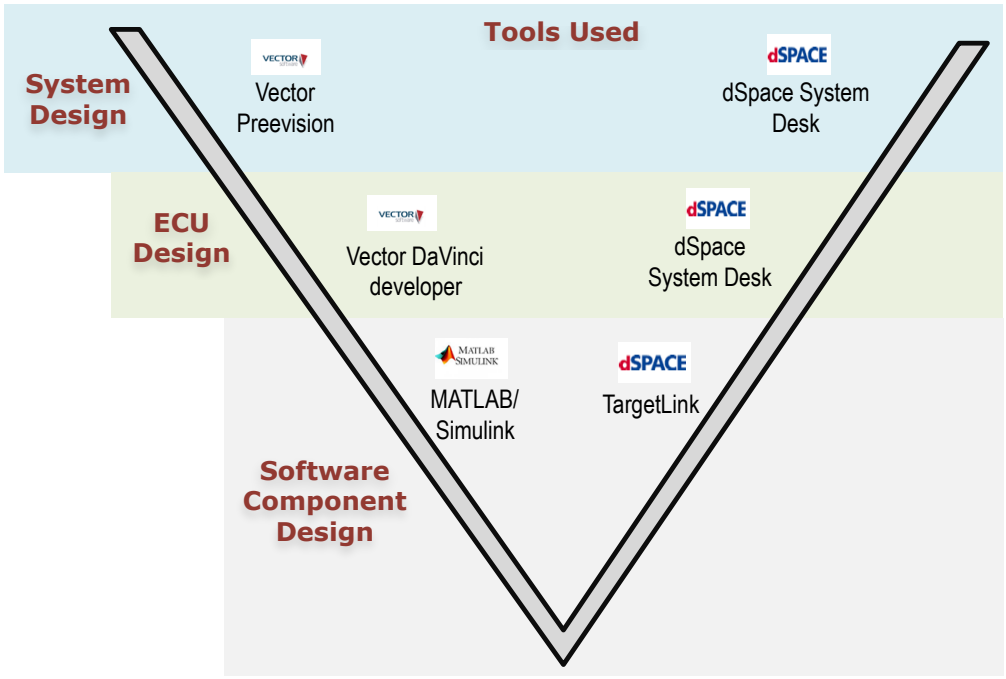


Figure 3.11: Software development workflow - AUTOSAR.

ARXML refers to the XML format specific to AUTOSAR environment. The AUTOSAR software development process roots in the generation of **System Description** ARXML file in the system design phase (Figure 3.11), which includes information about all the Electronic Control Units (ECUs) in a vehicle system and their interconnections. In the ECU design phase, the information about a particular ECU is derived as **ECU Extract**. This includes information about the list of SWCs in the ECU. Several network design tools from different vendors (e.g. Vector Preevision, dSpace SystemDesk, etc.) can be used for the System Description and the ECU Extract preparation. Further, in the SWC design phase, the information about the individual SWCs are filtered out as **SWC Description** ARXML files from the ECU Extract. By importing an SWC Description file in an AUTOSAR model development tool, the model algorithm can be developed. Alternatively, it is also possible to design an SWC from scratch using an AUTOSAR model development tool by defining the required port types. It shall also be noted that the SWC Description files are necessary for the RTE contract phase generation and integration with the BSW. The model development tools such as MATLAB/Simulink and TargetLink support AUTOSAR modelling and code generation in AUTOSAR format.

Furthermore, the workflows in the AUTOSAR model development process involving the SWC description files are shown in Figure 3.12. The **bottom-up** approach is the conversion of non-AUTOSAR models to AUTOSAR models and the generation of code and ARXML in AUTOSAR format. Alternatively, an SWC can also be modeled and exported as ARXML file from an AU-

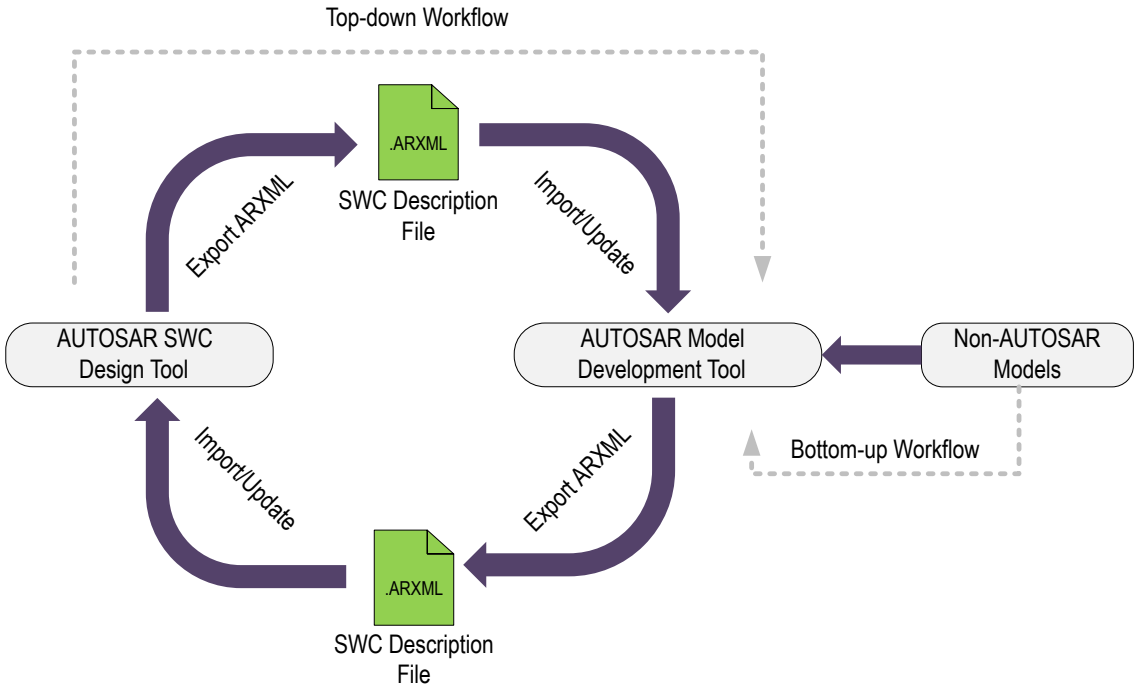


Figure 3.12: Workflows in AUTOSAR model development. Adapted from [30].

TOSAR design tool. This ARXML can then be ported into a model development tool to develop the model algorithm and generate model code respectively. This type of workflow is referred to as a **top-down** approach. Additionally, there is also **round-tripping** approach, wherein it is also possible to port back the SWC description file into the AUTOSAR design tool in case of any modifications (e.g. addition of an extra sender/receiver port) and update the model algorithm [29].

While converting a non-AUTOSAR model to AUTOSAR model, one must carefully ensure that the correct port interfaces and SWC types (Section 3.3.2) are mapped to the input and output ports of the non-AUTOSAR model. For example, the ports requiring NVRAM access must be configured as NV port types. Daehyun et al. [5] additionally mention that during the conversion process the ASW functionality of legacy software must be distributed among the AUTOSAR SWC types. Therefore, the model implementation involving sensor or actuator functionality must be configured as Sensor/Actuator SWC type; all the other application functionalities must be implemented in Application SWC type. During model development in the AUTOSAR environment, the developers must also be aware of the interaction rules among the various SWC types specified in the AUTOSAR specifications. An example of such interfacing rule is the ECU Abstraction component which can interact only with the Sensor SWC type and not directly with the Application SWC type for I/O access [8].

3.4.3 Differences in the Memory Mapping Approach

This section explains the differences in the memory mapping approach between the AVL HCU software and the AUTOSAR standard. In order to include the code entities (e.g. variables, function definitions, etc.) in the correct sections of the memory (e.g. data, text, etc.), the memory mapping keywords are included in the SWC code files. The AUTOSAR specification defines a format for the memory mapping keywords [31] (Appendix A). Additionally, these keywords are also remapped to the specific memory sections in a memory mapping header file, which is also included with the SWC code files. The variables and function (runnable entity) definitions are placed within the corresponding mapping keywords in the SWC code files. An illustration of the usage of memory mapping keywords in AUTOSAR format is shown in Listing 3.1, which provides an example of SWC code file *SeatHeatingControl.c* with variables (Lines 2 to 7) and the runnable entity definition (Lines 11 to 18) grouped according to the memory mapping information. The content of the corresponding memory mapping header file is shown in Listing 3.2. It can be seen that the mapping keywords in Listing 3.2 are undefined (Lines 3 and 8) after being remapped to the respective memory sections using *pragma* commands (Lines 2 and 7). As the *pragma* usage is compiler specific, the list of compilers that support this keyword is shown in [31].

Listing 3.1: SWC Code File: SeatHeatingControl.c

```
1  //Variable declaration
2  SHC_START_SEC_VAR_INIT_16
3  #include "SHC_Memmap.h"
4  static uint16 var1;
5  static uint16 var2;
6  SHC_STOP_SEC_VAR_INIT_16
7  #include "SHC_Memmap.h"
8  [...]
9  [...]
10 //Runnable definition
11 SHC_START_SEC_CODE
12 #include "SHC_Memmap.h"
13 void SeatHeatingControl (void)
14 {
15 //Some code lines
16 }
17 SHC_STOP_SEC_CODE
18 #include "SHC_Memmap.h"
```

Listing 3.2: Memory Mapping Header: SHC_Memmap.h

```
1  #ifdef SHC_START_SEC_VAR_INIT_16
2            #pragma memory section ".data"
3            #undef SHC_START_SEC_VAR_INIT_16
4  [...]
5  [...]
```

```
6 #ifdef SHC_START_SEC_CODE
7           #pragma memory section ".text"
8           #undef SHC_START_SEC_CODE
9 #endif
```

The memory mapping keyword format of the AVL HCU software is defined by the BSW supplier (Appendix B). Unlike the AUTOSAR format, the SWC prefix (<COMPONENT_PREFIX>) is not a part of the keyword format provided by the BSW supplier. Consequently, AVL can only adopt the same keyword format (from the BSW supplier) generically for all the SWCs present in the HCU software system, without differentiating the format for SWC-specific usage. However, in order to avoid the above scenario and to make the keyword format more distinct for SWC-specific usage, the mapping keywords have been remapped by AVL from supplier defined format to another format with the SWC prefix. A look at the memory mapping header file (Listing 3.3) used in the AVL HCU software provides an understanding of the above statement. Lines 1 and 4 in Listing 3.3 represent the keywords redefined by AVL with the SWC component prefix. These are also the mapping keywords used in the SWC code files. Lines 3 and 6 represent the format provided by the BSW supplier.

Besides, there are no major differences in the process of memory mapping and memory handling except for some naming conventions in the mapping keyword format, which are summarized in Table 3.3.

Listing 3.3: Memory Mapping Header used in AVL HCU Software: Memmap.h

```
1 #elif defined AHM_START_SEC_CODE_10MS
2    #undef AHM_START_SEC_CODE_10MS
3    #define ASW1_OEM_START_SEC_DEFAULT_CODE
4 #elif defined AHM_STOP_SEC_CODE_10MS
5    #undef AHM_STOP_SEC_CODE_10MS
6    #define ASW1_OEM_STOP_SEC_DEFAULT_CODE
```

Category	**Used in AVL HCU Software**	**Specified by AUTOSAR Standard**
File Name	Memmap.h	<Component>_memmap.h, wherein <Component> denotes the module abbreviation of the SWC.
SWC Module Abbreviation Prefix	<COMPONENT_PREFIX> is not included in the mapping keyword format provided by the BSW supplier; however, it is used in the keywords remapped by AVL.	<COMPONENT_PREFIX> is a part of the memory mapping keywords.
Variable Alignment Postfixes	8, 16, 32, UNSPECIFIED	8, 16, 32, PTR, UNSPECIFIED

Variable Initialization Postfixes	INIT, CLEARED	NO_INIT, CLEARED, POWER_ON_CLEARED, INIT, POWER_ON_INIT
Variable Data Sections Postfixes	DEFAULT, SMALL, SAVED_ZONE, CALIB, CONST	VAR, VAR_SLOW, VAR_FAST, VAR_SAVED_ZONE, VAR_SAVED_RECOVERY_ZONE, CONST, CALIB, CONFIG_DATA
Code Section Postfixes	CODE	CODE, CALL_OUT_CODE, CODE_FAST, CODE_SLOW.

Table 3.3: Some observed differences in the mapping keyword format between the AVL HCU software and the AUTOSAR standard.

Therefore, while converting a model to AUTOSAR, the memory mapping approach must be adapted to the AUTOSAR specified format in the generated code for the converted models, in order to facilitate integration with the generated RTE and the BSW.

3.5 Integration Level Deviation

3.5.1 Integration Process in AVL HCU Software

Once the model has been developed and tested in the MIL environment, it is subjected to code generation. The C code is auto-generated by the TargetLink and is generally the translation of the model algorithm, I/O signals and parameters from the Simulink model level to C code level. In the case of AVL HCU software models, the generated code files are *model *.c, *.h*, *model_input *.c, *.h* and *model_data *.c, *.h* files. All the parameters are directly read from the model data files. The included header files provide the I/O parameters with the global scope using the *extern* keyword. The model code files along with the CIL code and the BSW (compiled object files obtained from the supplier) have to be compiled in a build environment[4] and an ECU executable (binary file in *.hex* [32] format) can be generated. The compiler used for building the system is generally indicated by the supplier of the BSW and hardware. The build environment used in this case is Hightec compiler suite [33]. The reader can refer to Section 5.3 for more details on the build procedure.

3.5.2 Integration Process in AUTOSAR Software Models

According to the AUTOSAR methodology, the configuration and description ARXML files play a pivotal role in every phase of AUTOSAR system development and integration. In simple words, the configuration and system description information in the ARXML schema are portable across various AUTOSAR tools, and transferrable across the parties (OEMs and suppliers) involved in the AUTOSAR system development. A short overview of the AUTOSAR methodology and the related

[4]The build environment in this context refers to the complete toolchain set used in the compilation and linking of the SWC code files, leading to the generation of ECU executable, which can then be flashed in the ECU hardware.

ARXML files involved is shown in Figure 3.13.

While the System Description and the ECU Extract contain the architectural information regarding the system and the ECU, the ECU Configuration Description contains the configuration information necessary for the ECU integration. A rather detailed account of each ARXML file involved is shown hereinafter. The following sections are based on [34, 35].

System Description

As shown in Figure 3.14, the System Description is created from the SWC Description, System Constraint Description, and the ECU Resource Description. The SWC Description is the ARXML file representing the structure of an SWC with port interfaces without the model algorithm. As per [35], the ECU Resource Description represents the hardware specifications such as the memory requirements and pin assignments. The System Constraint Description specifies various limitations posed on the system with specific boundary conditions. The System Description, in general, represents the whole system architecture, including all the ECUs present in the system, the related SWCs present within each ECU and the interconnections among them in the ARXML schema. The System Description also includes communication information among the ECUs such as the protocols involved (CAN, LIN or FlexRay), and the entities to be transferred (message and signal architecture). In general, the System Description is prepared at the OEM side after analyzing the system constraints and the resource requirements. Network design tools such as Preevision [36] is an example of the tools to be used for the preparation of System Description.

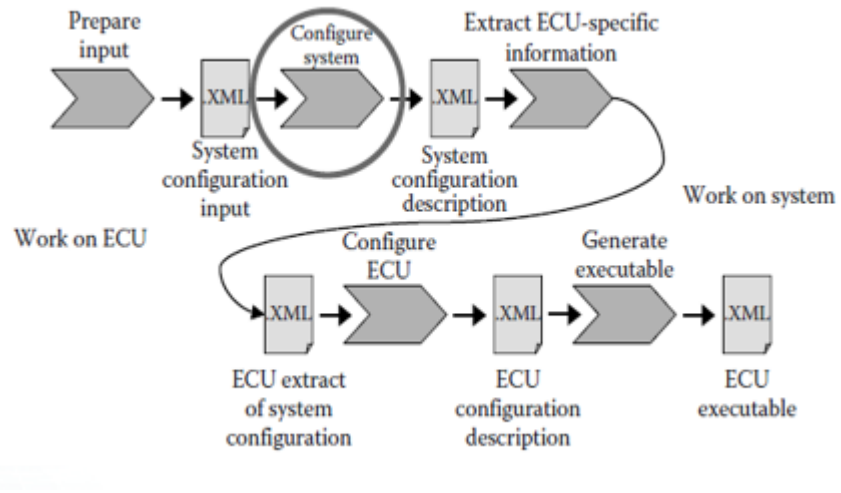


Figure 3.13: AUTOSAR methodology [2].

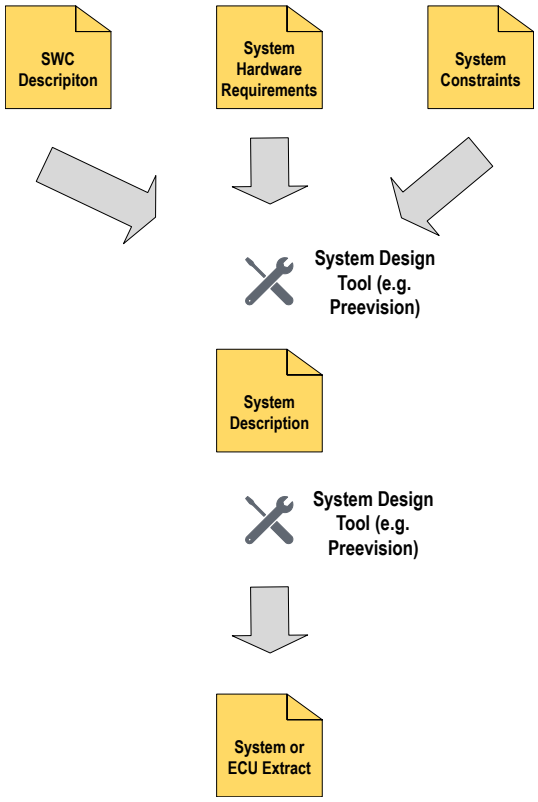


Figure 3.14: Preparation of System Description and ECU Extract. Adapted from [35].

ECU Extract

The ECU Extract includes information related to specific ECUs: SWCs mapped to the specific ECU, the interconnections among the SWCs via ports for intra-ECU communication, and the communication protocol involved in the communication over the ECU boundary. In general, the ECU Extract is considered as a subset of the information present in the System Description. The system design tool (e.g. Preevision) can be used in this case to prepare the ECU Extract from the System Description. The ECU Extract is also prepared by the OEM and is generally provided to the suppliers of the respective ECUs. The suppliers use the SWC information from the ECU Extract to develop the ASW model algorithms for a particular ECU [35].

BSW Module Description

According to [34], the BSW Module Description (BSWMD) is an ARXML format file that contains the definitions of the parameters to be configured during the configuration phase. It is to be noted that the BSWMD is supplied as one of the inputs to the configuration tool. The tool refers to the BSWMD for the definition and the list of permissible values assignable to a parameter. An example

of parameter definition from [15] is shown in Table 3.4.

Parameter Definition	
Name	ComIPduCallout
Parent Container	ComIPdu.
Description	"This parameter defines the existence and the name of a callout function for the corresponding I-PDU. If this parameter is omitted no I-PDU callout shall take place for the corresponding I-PDU."[15]
Multiplicity	1

Table 3.4: An example of parameter definition ([15], p.1014).

The BSWMD is included by the supplier of the BSW in the scope of delivery of the BSW stacks. The supplier also chooses to include optional vendor-specific parameters in the BSWMD, if required, in the ARXML schema [34].

ECU Configuration Description

The ECU Configuration Description is the result of the configuration process generated from the configuration tool. The file is normally of 5 to 10 MB in size, in ARXML format, and contains the configured parameters of the RTE, OS, COM and all the BSW modules [34]. The configured

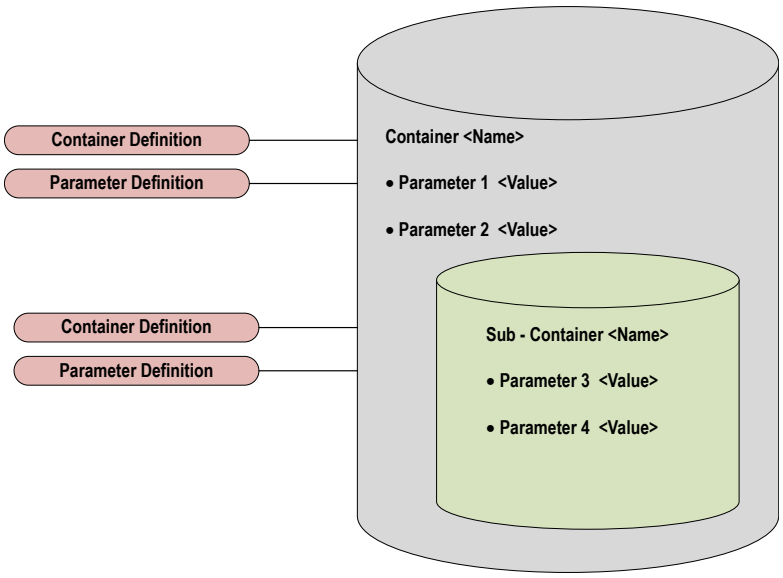


Figure 3.15: Structure of ECU Configuration Description. Adapted from [34].

parameters are housed as **containers** and **sub-containers** and refer to the parameter definitions obtained from the BSWMD. A container is generally an encapsulation of the parameters and the related definitions. A container can additionally include a sub-container [34]. The structure of the ECU Configuration Description can be noted in Figure 3.15. As can also be noted from Figure 3.16, the ECU Configuration Description is a prerequisite for the generation of the RTE and BSW configuration codes.

Configuration Generation

The BSW configuration is a necessary step to be performed in the AUTOSAR integration process resulting in the generation of the RTE and the BSW configuration code files. The BSW stacks are delivered by the BSW supplier (supplier of the AUTOSAR BSW stacks, e.g. Vector) along with the tools necessary for configuration. A configuration tool (e.g. DaVinci Configurator Pro from Vector [37]) provides the necessary platform to configure every BSW module individually. The parameters to be configured are displayed as containers in the tool window, in which the user can set the desired value of a parameter from the parameter definitions using a drop-down box.

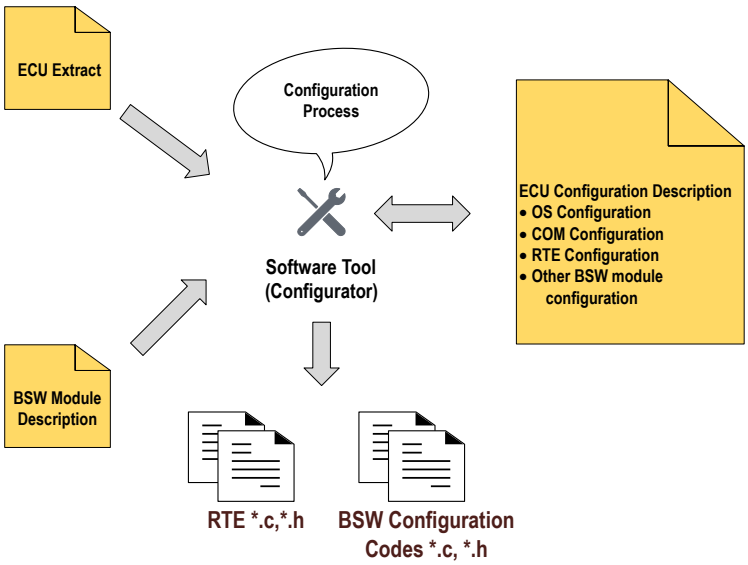


Figure 3.16: Configuration process: Generation of ECU Configuration Description and configuration code files. Adapted from [34].

In general, there are more than 1000 BSW module parameters to be configured, as per [34]. The configuration tool reads in the ECU Extract and the BSWMD and presets some of the parameters automatically [34] (Figure 3.16). The other parameters can be set by the user and the Base ECU Configuration Description (Base ECUC) can be generated. The Base ECUC can be further modified for the finalization of the configuration, and thereafter the ECU Configuration Description is produced [38]. Additionally, the RTE and the BSW configuration codes are also generated by the

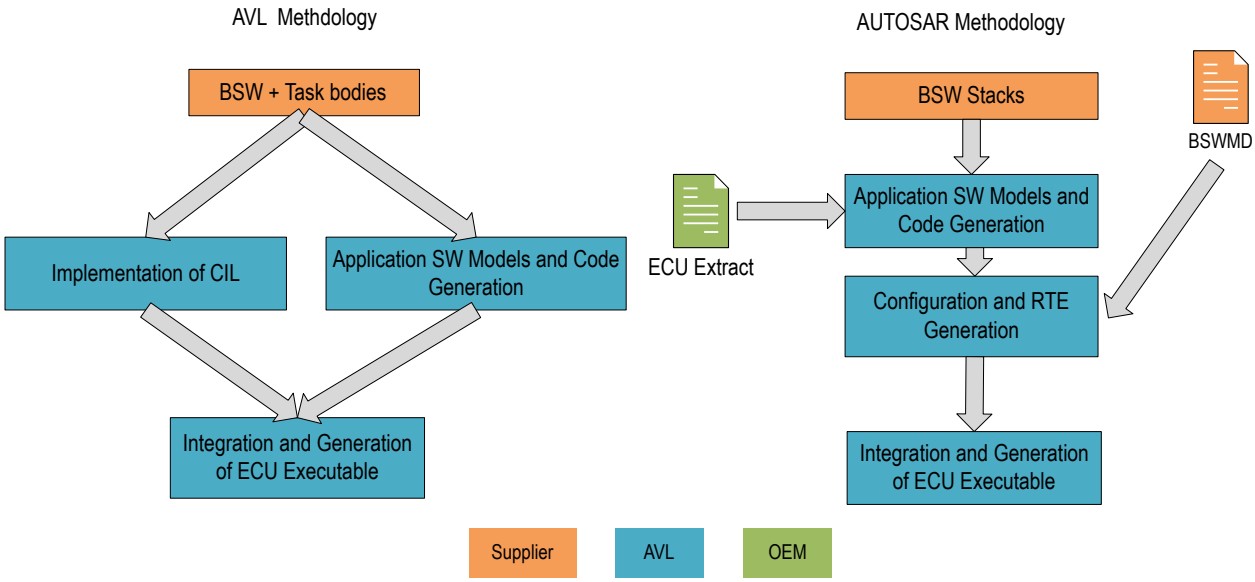


Figure 3.17: Comparison of software development methodology between AVL HCU software and AUTOSAR software models.

configuration tool from the ECU Configuration Description.

It is also noteworthy mentioning that the BSW module parameters can fall into different configuration classes: **pre-compile time, link-time and post-build**, which determine the time in which the BSW parameters are finalized in the build process [39]. The pre-compile time and the link-time parameters are fixed during the compilation and the linking phase of the BSW module code[5] respectively, while the post-build parameters are set only during the ECU boot phase [39]. The reader can additionally refer to [40] for more information on configuration classes.

Integration and Executable Generation

The next step involves the integration and executable generation. The BSW configuration code files generated by the configuration tools along with the BSW module code files, RTE code files, and SWC code files are compiled and built in a build environment. Once the system is built successfully, the ECU executable can be generated as a binary file (*.hex*) which can be flashed in the ECU hardware. Regina in [39] additionally mentions that the handling of BSW parameters in the build process varies with different configuration class types introduced previously. For example, the pre-compile time parameters have to be compiled along with the BSW module code files, while the post-build and link-time parameters have to be supplied as compiled object files for linking with the BSW module code in the generation of ECU executable [39].

[5]The BSW module code in this context refers to the BSW static source delivered by an AUTOSAR BSW supplier (e.g. MICROSAR from Vector [41])

3.6 Comparison of Development Methodology

This section summarizes the current software development methodology of AVL and the steps to be followed if AUTOSAR methodology is to be adopted by AVL. As per Figure 3.17, in the development methodology of AVL HCU software, the supplier implements the BSW and the task bodies, whereas the ASW modelling, code generation and the implementation of CIL layer are handled by AVL. If the AUTOSAR approach is to be followed, the supplier needs to deliver the configurable BSW stacks along with the BSWMD and toolchains necessary for the BSW configuration and integration. In AUTOSAR case, AVL shall be responsible for the ASW model development, BSW configuration, RTE generation as well as the integration with BSW. The customer OEM may additionally supply the ECU Extract with the SWC information necessary for the ASW model development.

4. Implementation Approach

This chapter explores the choices of implementation based on some boundary conditions and outlines the approach followed in this thesis for AUTOSAR conversion.

4.1 Implementation Decisions

As the deviations with respect to AUTOSAR standard have now been analyzed for the AVL HCU software, the approach for conversion had to be based upon some boundary conditions such as resource availability, toolchain capability, licensing constraints, etc. The evaluation of the available toolchains has been carried out for ASW conversion and RTE generation. Additionally, the compatibility of the AVL HCU software's BSW has also been analyzed for reuse in the AUTOSAR conversion process.

4.1.1 Evaluation for Application Software Conversion

This section evaluates some of the MBD tools for ASW conversion to AUTOSAR format. MATLAB and TargetLink are the standard MBD tools widely used in the application for ASW modelling and code generation. As discussed in Section 3.4.1, the AVL software models were originally developed using MATLAB 2013b and TargetLink 3.5. In the proposed scenario, MATLAB 2017b (with Simulink and Embedded Coder) and TargetLink 3.5[1] have been used for ASW model conversion to AUTOSAR format. Both tools support all types of AUTOSAR workflows. With TargetLink, however, the AUTOSAR properties such as ports and runnable entities have to be configured manually for each and every model. There is no support offered by the TargetLink environment for automating the conversion. This proves to be costlier in terms of effort, especially when huge number of models are to be converted. Additionally, a valid TargetLink license for AUTOSAR type code generation was not procured for this project due to commercial reasons. Although it is possible to generate SWC model code in AUTOSAR format with this license, the TargetLink models have to be configured manually for AUTOSAR conversion and code generation.

[1] This has been the latest version being in use at AVL when this work was performed.

In comparison, the MATLAB/Simulink environment offers programmatic features with dedicated AUTOSAR specific APIs for automating the model conversion to AUTOSAR format [45]. In addition, the Embedded Coder environment can generate code in AUTOSAR format with the add-on 'AUTOSAR support package' installed. The programmatic features are quite convenient when the conversion has to be handled automatically using MATLAB scripts. In converting the legacy application to AUTOSAR, Daehyun et al. [5] have used MATLAB for migrating the ASW models of an interior lighting system to AUTOSAR format. However, there is no clear indication of automation being applied in this work. James at al. [6] additionally recommend MATLAB for a simpler and quicker way of automating the ASW conversion and have employed MATLAB scripts to convert a body control application to AUTOSAR format. The authors in [6] have used wrappers to convert the normal Simulink port types to AUTOSAR port types. The usage of wrapper blocks is however not required with the recent versions of MATLAB (with the 'AUTOSAR support package') that support AUTOSAR type model development. The authors in [6] also stress upon the need for automation when a large number of ASW models are involved. We preferred MATLAB to TargetLink in this thesis due to its support for automation and a large number of about 40 ASW models of HCU software system were subjected for AUTOSAR conversion.

4.1.2 Evaluation of Basic Software for Integration

It was decided to reuse the original BSW of the AVL HCU software for AUTOSAR conversion since AUTOSAR specific BSW stacks and the related configuration tools were not procured for this project due to commercial reasons. As mentioned in Section 2.2.4, the BSW structure used in AVL HCU software is not AUTOSAR compliant. Nevertheless, the BSW possesses the required features supporting the integration with an AUTOSAR ASW. For example, the task bodies provided by the BSW supplier can be used to schedule ASW runnable entities, and the supplier-specific API interfaces from the BSW can still be integrated with the AUTOSAR ASW via an interfacing middleware.

4.1.3 Evaluation for Run Time Environment Generation

According to AUTOSAR, the RTE layer contains function definitions for resolving the SWC port communication and task bodies for scheduling the runnable entities (Section 2.1.2). It can be noted that the BSW architecture of the AVL HCU software, which is to be reused for AUTOSAR conversion, already contains some of the features of the RTE, such as the task bodies (Figure 2.9) provided by the BSW supplier, which can schedule the ASW runnable entities. Thus, the aim is to generate the RTE portion involving only ASW communication. The RTE generation capability has been evaluated using DaVinci developer[2]. DaVinci developer [42] is a Vector proprietary tool primarily used for ECU and SWC design. As we found out that the tool can only generate RTE contract phase header files with the code generation option, we decided to implement an RTE generator engine in MATLAB based on [7], which can generate the RTE function definitions involving ASW communication.

[2]We could evaluate only DaVinci developer since it was procured by AVL as an evaluation package for a customer project. Other RTE generator tools were not procured due to commercial reasons.

4.2 Conversion Approach towards AUTOSAR Compliance

Figure 4.1 illustrates the conversion approach used in this thesis. The Application SWCs and the communication features among them are already converted to AUTOSAR format (with the RTE portion generated). The original non-AUTOSAR BSW of the AVL HCU software has been reused for integration. Additionally, since the CIL contains functionalities related to CAN signal checks and other signal mappings (Section 2.2.3), replacing the layer can be costlier in terms of manual modifications needed in the code level. Hence we have decided to retain the CIL layer. The interfaces between the CIL and the BSW have not been modified; therefore these interfaces are not AUTOSAR conformed. The proposed conversion approach can still promise ICC1 AUTOSAR conformance level, although fullest AUTOSAR ICC3 conformance is not possible. The ICC1 conformance category states that the BSW along with the RTE implementation is proprietary, which can be considered as a single black-box unit, and that only the SWC communication and the interfaces with this black-box unit need to be AUTOSAR conformed. In the proposed approach (Figure 4.1),

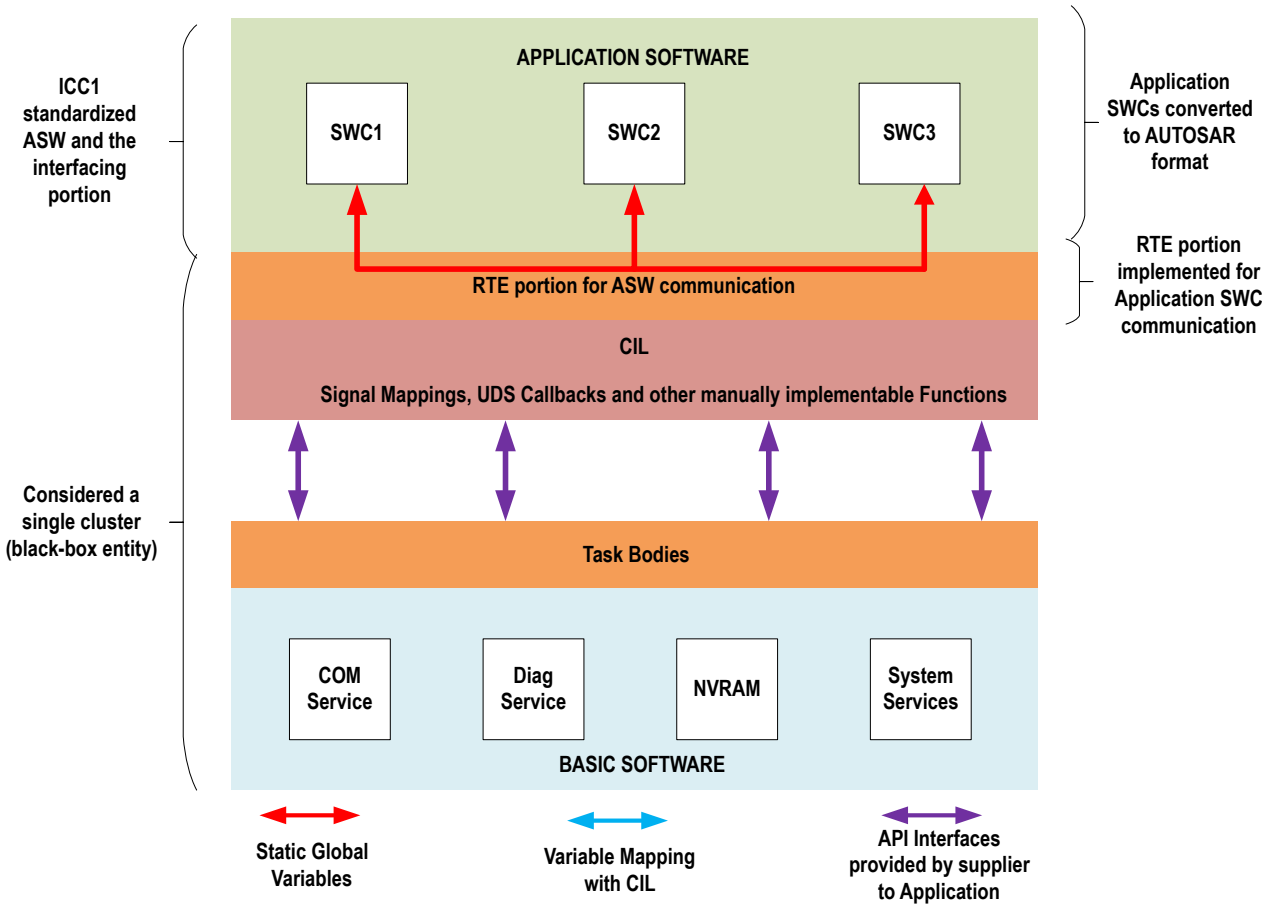


Figure 4.1: AUTOSAR conversion approach used in the thesis.

the RTE portion along with the CIL and the BSW can be considered as a single unit, interfaced with the Application SWCs converted to AUTOSAR format. Daehyun et al. [5] additionally mention that if a non-AUTOSAR BSW has to be reused for AUTOSAR migration, only an AUTOSAR conformance of ICC1 or ICC2 can be achieved and that only a new AUTOSAR specific BSW modules have to be used if implementation conformance of ICC3 is targeted. Thus the proposed AUTOSAR conversion approach cannot meet ICC3 conformance requirements however, it can conform to ICC1 category. Some of the features in the proposed concept which are not conformed according to ICC3 requirements are summarized in Table 4.1.

Category	**Proposed AUTOSAR Conversion Concept**	**AUTOSAR ICC3 Requirements**
I/O Signal Access	The presence of I/O Hardware Abstraction layer is not explicit in the BSW implementation. I/O signals are accessed via the supplier defined API interfaces from the BSW and routed via the CIL to the ASW.	I/O Hardware Abstraction SWC type in the BSW is used for I/O signal access (Section 3.3.2).
BSW-RTE Interfaces	Only the RTE portion involving Application SWC communication is AUTOSAR conformed. The interfaces to the BSW are not conform with AUTOSAR due to the presence of the CIL layer.	The RTE-BSW interaction involves standardized API calls (Section 3.3.2).
Scheduling of Runnable entities	The task bodies used in the runnable scheduling are part of BSW implementation from the supplier. The RTE events are however not part of BSW implementation and are not used in the scheduling of runnable entities. The scheduling approach is the same as that used in the original AVL HCU software (Section 3.3.3) since the CIL and the BSW implementations were retained.	The task bodies are configured in the RTE configuration step and generated as part of the RTE generation. The invocation of runnable entities may also depend on RTE events (Section 3.3.3).
Development Methodology	AUTOSAR methodology has not been followed. The configuration step of the BSW is not needed since the BSW is pre-configured by the supplier.	The development process must follow the AUTOSAR proposed methodology from scratch. The configuration of the RTE and the BSW is a necessary step in software integration.

Table 4.1: Some of the features which are not AUTOSAR conformed as per ICC3 requirements in the proposed conversion approach.

5. Implementation

In Chapter 3, the software deviations from the AUTOSAR standard have been analyzed, and in Chapter 4, the concept for AUTOSAR conversion has been put forth. This chapter focuses on the implementation part to incorporate the HCU software with AUTOSAR features.

5.1 Model Conversion to AUTOSAR

This section deals with the conversion of ASW models of AVL HCU software to AUTOSAR format. MATLAB provides a licensed 'AUTOSAR support package' for model development in AUTOSAR environment and also for the conversion of non-AUTOSAR models to AUTOSAR format. MATLAB also ensures that the model conversion to AUTOSAR format can be handled programmatically without the need for manual configuration of each model. As analyzed in Section 4.1.1, the programmatic feature has been preferred in this thesis, since a software system of HCU comprising of about 40 models are to be converted to AUTOSAR format. A cascade of MATLAB scripts was used to automate the model conversion and code generation in AUTOSAR format. In a nutshell, the model conversion process involves the following steps:

1. Removal of TargetLink properties.
2. Generation of new model libraries with *._Lib* suffix.
3. Extraction of AVL software models from the Maestra framework.
4. Applying AUTOSAR conversion.

Figure 5.1 illustrates the steps involved in the ASW conversion process and the by-products after each step. MATLAB scripts were developed to handle each of the above-mentioned steps. The TargetLink models indicated in the first step of Figure 5.1 are the state of the art development models of the non-AUTOSAR AVL HCU software. The sections hereinafter provide a detailed description of the scripts involved and the results observed after each conversion step. The script files are shown as excerpts in the form of listings.

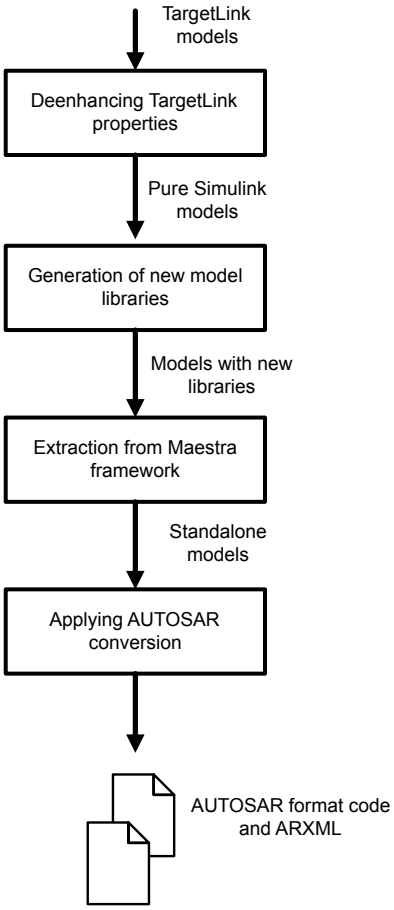


Figure 5.1: ASW conversion flow.

5.1.1 Removal of TargetLink Properties

The original AVL HCU software models were developed using TargetLink blocks. In order to handle the models in the MATLAB/Embedded Coder environment, the TargetLink property has to be removed, which is generally the replacement of TargetLink blocks in the model with the equivalent Simulink blocks. This step is necessary since the code generation for the AUTOSAR converted models are to be handled in the Embedded Coder environment. The MATLAB script *DeEnhanceTlProp.m* was developed for the purpose of removing the TargetLink properties. Figure 5.2 provides a general understanding of the program flow.

Code and Explanation

The script is invoked as a function call from the MATLAB command window. MATLAB 2013b has been used in this case, since it is supported by TargetLink 3.5 using which the AVL software

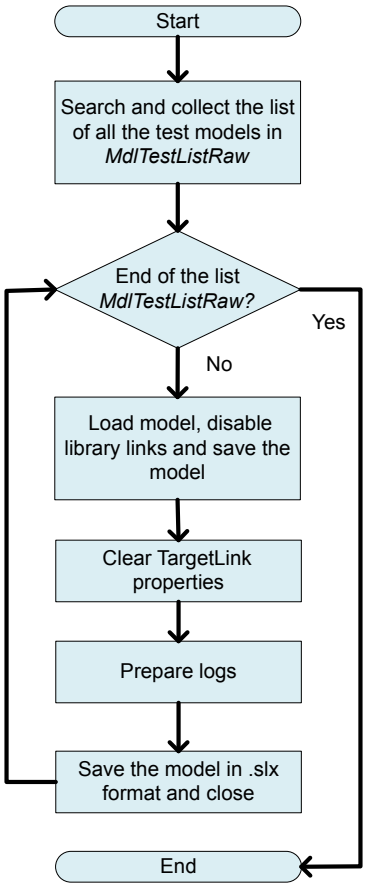


Figure 5.2: Program flow: DeEnhanceTlProp.m

models have been developed. The project path[1] (Line 1 of Listing 5.1) of the AVL software models is provided as an argument to the function. The part of the code in Listing 5.1 searches all the models saved with the suffix *_Test.mdl*. As indicated in Section 3.4.1, the test models are the ones that link with the model libraries and are loadable within the Maestra framework for MIL simulation. The function *subdir* in Line 4 of Listing 5.1 is used to collect the list of all the test models present in the project directory.

Listing 5.1: DeEnhanceTlProp.m - Collection of test model list.

```
1 function str = DeEnhanceTLProp(FolderPath)
2 [...]
3 %% Search for all the test models
4 MdlTestListRaw = subdir([Dereflink.Projectpath '\*_Test.mdl']);
5 [...]
```

[1]The folder path to the AVL HCU software project directory which contains all the ASW model implementations.

Listing 5.2: DeEnhanceTlProp.m - Saving the models by disabling the library links.

```
1 [...]
2 %% Break links and save the model
3 save_system(TestMdlNameName, [TestMdlPath '\' TestMdlNameName], 'BreakLinks')
4 load_system(TestMdlNameName);
5 open_system(TestMdlNameName);
6 [...]
```

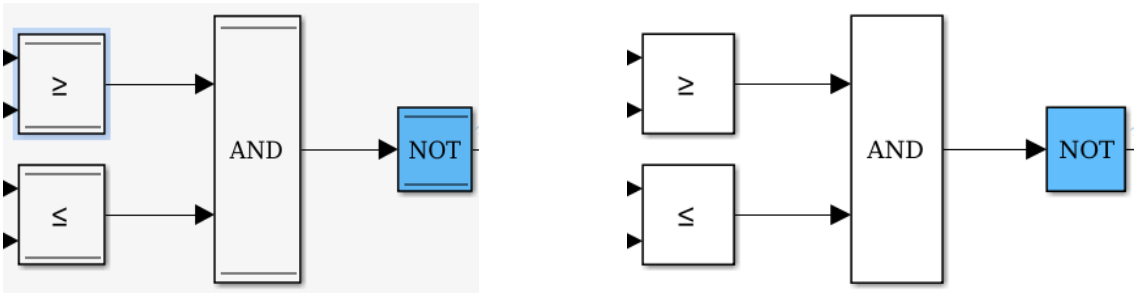
The script in the next step goes through the list of all the test models and saves the model by breaking the library links (Line 3 of Listing 5.2). This step is performed to unlock the library links to the model libraries, so that the <*Model_Test*>*.mdl* can be edited.

Listing 5.3: DeEnhanceTlProp.m - Clearing TargetLink properties.

```
1 [...]
2 %% Applying deenhancement of TargetLink properties
3 [options, msg] = tl_clear_system('system', TestMdlNameName);
4 [...]
```

In the next step, the deenhancement of TargetLink properties is applied. The *tl_clear_sytem* (Appendix C) is the MATLAB API provided by the TargetLink for the removal of TargetLink blocks from the system. The API also returns logs of the function in the form of structure, which can be used to verify the results of deenhancement from TargetLink blocks. The usage is shown in Line 3 of Listing 5.3. The logs are also stored as excel files. After the application of deenhancement, the model is saved in .slx format and the function continues with the next iteration in the list of models.

Results



A. Before Deenhancement (TargetLink Blocks)

B. After Deenhancement (Simulink Blocks)

Figure 5.3: Model block properties before and after deenhancement.

All the test models were removed from TargetLink properties. Figure 5.3 compares the model properties before and after deenhancement. For illustrative purpose, only a subset of model blocks (AND, NOT and relational operator blocks) from the model implementation is considered in Figure 5.3. Figure 5.3A shows the TargetLink blocks before deenhancement, while the same blocks after

deenhancement are replaced with the equivalent Simulink blocks in Figure 5.3B. An excel log file is also generated for each model after the deenhancement has been applied.

5.1.2 Generation of New Model Libraries

Once the TargetLink features are removed from the test models, new model libraries have to be generated with respect to the newly replaced Simulink blocks. The new model library can be generated by opening the Maestra session file (.AVLab file) of a deenhanced test model and selecting the option 'Create new library', which creates a new library *Model_Lib* in the *.slx* format. As this process is to be accomplished for the entire software system, MATLAB script *CreateLibrariesBatch.m* was developed to expedite the library creation for all the available test models. This script has been executed in MATLAB 2017b so that the newly generated model libraries are generated in *.slx* format by default. The process flow of the script is shown in Figure 5.4.

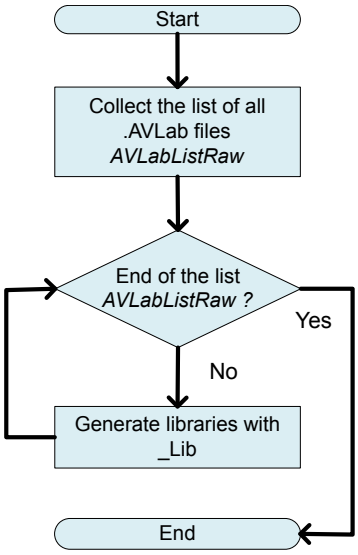


Figure 5.4: Program flow: CreateLibrariesBatch.m.

Code and Explanation

The project directory, which now contains the deenhanced test models from the previous step, is passed as an argument to the function *CreateLibrariesBatch.m*. As per Figure 5.4 and Listing 5.4, in the first step, the function *CreateLibrariesBatch.m* searches and collects the list of all the Maestra session (.AVLab) files present in the project directory (Line 2 of Listing 5.4).

Listing 5.4: CreateLibrariesBatch.m - Creation of new model libraries.

```
1  %% Check for all .AVLab files
2  AVLabListRaw = subdir([Dereflink.Projectpath '\*.AVLab']);
3  OutputsTotal = length(AVLabListRaw);
4  %% Create libraries
5  for idx=1:length(AVLabListRaw)
6      try
7          AVLabses_load(AVLabListRaw(idx).name);
8      catch ME
9          ME.message;
10     end
11     mil_createlib();
12 end
```

In the next step, the script goes through the list of the .AVLab files and loads the test model within the Maestra framework. Subsequently, the *mil_createlib()* is invoked to create new model libraries. The usage is shown in Line 11 of Listing 5.4. The MATLAB function *mil_createlib()* is associated with the Maestra framework and generates the libraries of the deenhanced models. The new model libraries are generated with the naming convention *Model_Lib* for all the models since this setting is adopted by default in the latest version of Maestra.

Results

Figure 5.5: An example of a new model library generation.

The new model libraries have now been generated. Figure 5.5 shows an example folder content of a particular SWC model before and after the generation of the new model library. The files listed in Figure 5.5A are the original model library (marked with 'black' outline) and the model data files (.dd and _data.m files). Figure 5.5B shows the contents of the same SWC model folder with the newly created model library in .slx format.

5.1.3 Model Extraction from Maestra Framework

In this section, the extraction process of the model from the Maestra framework has been explained. As indicated in Section 3.4.1, the AVL software models are embedded within the Maestra framework integrated with TargetLink and MATLAB. Since the AUTOSAR code generation is to take

place solely in the Embedded Coder environment, the models must be extracted as standalone models. This step is necessary since the Simulink models with Maestra interface layers cannot be adopted for AUTOSAR format code generation. The top layers which form the interface layers to the Maestra environment are removed leaving the model with I/O ports and a subsystem with the model implementation. The extraction from Maestra framework is also a part of the delivery process of AVL software models to the customers. The scripts used for the model delivery are also called as delivery scripts. The following scripts are involved with the extraction of models from the Maestra framework[2]:

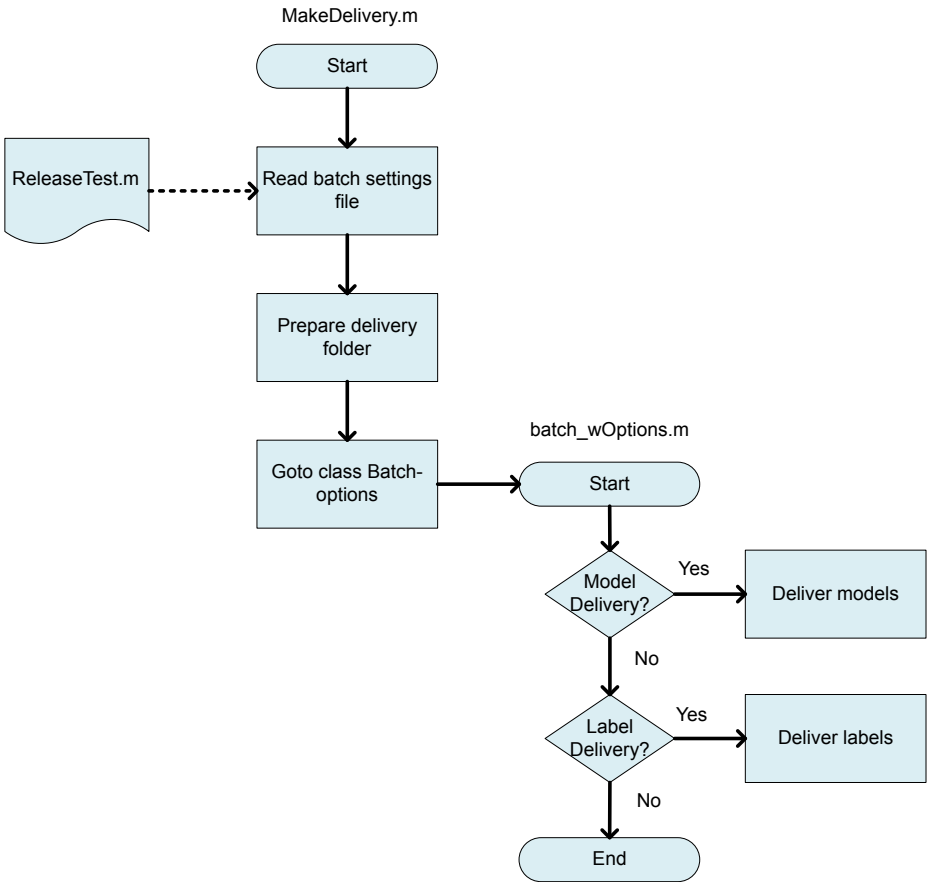


Figure 5.6: Program flow - Extraction of models from Maestra framework.

- The MATLAB script file *ReleaseTest.m* indicates the batch setting file for model delivery.
- The MATLAB script file *MakeDelivery.m* initializes the folder for the delivery process.
- The MATLAB class implementation *batch_wOptions.m* executes various batch options set for delivery.

[2]The delivery scripts were originally developed by AVL and have been used in this thesis.

The code files are explained in excerpts in the following section.

Code and Explanation

Figure 5.6 provides an understanding of the program flow of the delivery scripts used for model extraction from the Maestra framework. The script file *ReleaseTest.m* provides the batch settings for the options to be executed by the class file *batch_wOptions.m*. An excerpt from *ReleaseTest.m* is shown in Listing 5.5 showing various options for the settings to be set for the delivery process. The setting file *ReleaseTest.m* is instantiated in the constructor of the class *batch_wOptions.m*.

Listing 5.5: ReleaseTest.m - Batch options for the model delivery process.

```
1  %Setting for data file delivery
2  settings.EnaCalDelivery = true;
3  [...]
4  %Setting for calibration file delivery
5  settings.EnaDataDelivery = true;
6  [...]
7  %Setting for model delivery
8  settings.EnaModelDelivery = true;
9  [...]
10 %Setting for label delivery
11 settings.EnaLabelDelivery = 'full';
```

Listing 5.5 indicates that the batch settings for the delivery of the model, data and calibration files are set to **true** (Lines 2,5 and 8). The setting of label delivery to *'full'* (Line 11) delivers the signal and parameter list to be used in the model as .xlsx files. For the models to be delivered, it is necessary to enable these options in the delivery process. The *ReleaseTest.m* is also stored in the project directory under the folder named **PrjCfg**. Listing 5.6 includes the option setting in *ReleaseTest.m* where the paths of .AVLab session files of the models to be delivered are placed (Lines 2 to 5). These are also the models to be removed from the Maestra framework. Additionally, the library path is also included which includes some Simulink libraries to be used in the models (Lines 8 to 10).

Listing 5.6: ReleaseTest.m - Maestra session file (.AVLab) paths of the various models to be delivered.

```
1  %.AVLab session file paths
2  settings.AvlabSessionFiles = {...
3  'ASW\ObsrEStorg\ObsrHvbat\ObsrHvbat.AVLab'
4  'ASW\LatCtlr\TracTqLimn\TracTqLimn.AVLab'
5  };
6  [...]
7  %Library paths
8  settings.AdditionalFiles = {...
9  'ASW\Lib\ProjLib\ProjectLib.slx'
10 };
```

The cascade of make delivery scripts is executed by invoking the script file *MakeDelivery.m* from MATLAB command window by passing the project path as an argument to the function call. As also indicated in Figure 5.6, the setting file *ReleaseTest.m*, present in the **PrjCfg** folder in the project directory, is read by the script *MakeDelivery.m*. This is also shown in Line 6 of Listing 5.7. Additionally, the user is also provided with an option to select one of the setting files, if multiple setting files are available in the **PrjCfg** folder.

Listing 5.7: MakeDelivery.m - Read batch setting file ReleaseTest.m.

```
1 % Get PrjCfg folder path
2 SettingsDirPath = fullfile(PrjRoot, 'PrjCfg', 'MakeDelivery');
3
4 if isdir(SettingsDirPath)
5   % Get the list of MATLAB files in Prjcfg folder path
6   SettingsDirList = what(SettingsDirPath);
7  [...]
8 end
```

Further, in Line 3 of Listing 5.8 of *MakeDelivery.m*, the delivery folder is prepared, which is also the folder where the standalone models are copied. The program flow is then transferred to the execution of the class file *batch_wOptions.m*, as shown in Line 2 of Listing 5.9. The class *batch_wOptions.m* is responsible for executing various batch options based on the batch settings in *ReleaseTest.m*. It is also in this part of the program execution that the model .AVLab session file paths placed in *ReleaseTest.m* are read in (Line 4 of Listing 5.9).

Listing 5.8: MakeDelivery.m - Preparation of delivery folder.

```
1 % Clean up and create the delivery folder
2 if ¬isdir(DeliveryDir)
3     mkdir(DeliveryDir);
4 end
```

Listing 5.9: MakeDelivery.m - Transfer execution to class batch_wOptions.

```
1 %Initialize constructor of class batch_wOptions
2 batchobj = eval('batch_wOptions(settings)');
3 % Additionally include .AVLab files of the models to be delivered
4 mil_runbatch(batchobj, settings.AvlabSessionFiles, settings.LogFilePath);
```

The class file *batch_wOptions.m* description is shown in Listing 5.10 and Listing 5.11. Listing 5.10 shows the class definition with the batch options as the properties and the various batch settings from *ReleaseTest.m* initialized in the constructor definition. Listing 5.11 further indicates the method definition to process the extraction of models from the Maestra framework.

Listing 5.10: batch_wOptions.m - Class body and constructor initialization.

```
classdef batch_wOptions < batch_template
  %   Class body for the execution of delivery batch options
  %   - Creates a delivery model
  %   - Zips all delivery models to a delivery folder

  properties
  % data and calibration
  EnaCalDelivery
  EnaDataDelivery
  EnaLabelDelivery
  [...]
  % models
  EnaModelDelivery

  methods
  %Constructor initialization
  function obj = batch_wOptions(PreSettings)
    % data and calibration
    obj.EnaCalDelivery   = PreSettings.EnaCalDelivery;
    obj.EnaDataDelivery  = PreSettings.EnaDataDelivery;
    obj.EnaLabelDelivery = PreSettings.EnaLabelDelivery;

    % models
    obj.EnaModelDelivery    = PreSettings.EnaModelDelivery;
```

Listing 5.11: batch_wOptions.m - Method definition for model extraction from Maestra.

```
%% Deliver Model as IOLayer Model or Library only
if obj.EnaModelDelivery
    if obj.EnaModelDelivery == true
        % Create the delivery model
        [suc(end+1), msg{end+1}, ¬] = Delivery.createIOLayerMdl(ses, ...
            obj.dsSearchDepth);
        msg{end} = sprintf('Model\n%s\n', msg{end});
end
```

The function *createIOLayerMdl()* (Line 5 of Listing 5.11) is associated with the Maestra framework for processing the .AVLab session files as standalone models with single I/O layer removing the interface layers to Maestra.

Results

The models were extracted from the Maestra framework and the delivered SWC entities such as the extracted models, the model libraries, the data files, and the labels were copied to the delivery folder. An illustration of the extracted model is shown in Figure 5.7[3]. It can be seen that the Maestra interface layer forms the top layer in the original AVL HCU software models (Figure 5.7A). The

[3]The original model files could not be used for a clear representation. Hence image illustration has been used here.

deenhanced Simulink model is shown as an 'orange' block in Figure 5.7. After the extraction process, the Maestra interface layers are removed and the model subsystem is extracted as a standalone model, as shown in Figure 5.7B. This standalone model can be subjected to AUTOSAR conversion in the next step. An example of the top layer model subsystem without the Maestra interface layers as seen in Simulink window is additionally shown in Figure 5.8. The text in Figure 5.8 represent various model I/O signals.

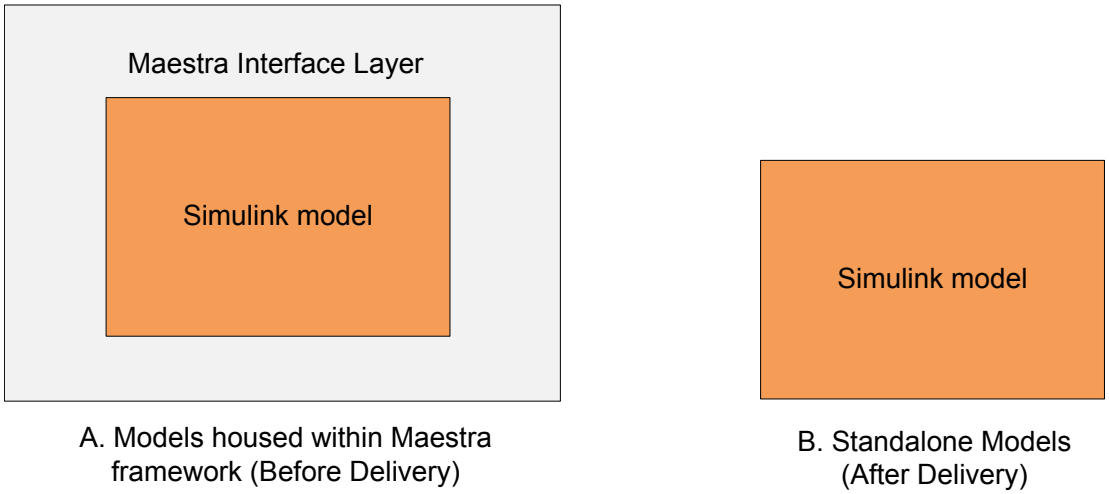


Figure 5.7: Models before and after extraction from Maestra framework.

A label file in .xlsx format is delivered for each model which provides information about the labels (I/O signals and parameters) used in the model implementation. The information contained in the label file of a particular model is summarized in Table 5.1.

Label Fields	**Description**
Name	Indicates the name of the signals/parameters used in the model.
Description	Provides a short description of the parameters/signals used in the model.
Type	Indicates the type of the labels used in the model (e.g. *Online* for signals; *Parameter* for parameters).
Classification	Indicates the scope of the signals/parameters used in the model (e.g. *Local* for local signals/parameters; *Input/Output* for I/O signals/parameters).
Datatype	Indicates the data type of the parameters/signals used in the model (e.g. *uint8*).

Value Range	Indicates the range of values in the hexadecimal notation for parameters/signals used in the model (e.g. *0* to *FF* for signal/parameters with type *uint8*).
Memory Range	Indicates memory range in the hexadecimal notation for parameters/signals used in the model (e.g. *0* to *255* for signal/parameters with type *uint8*).
Source Component	Indicates the source of the signals/parameters used in the model.

Table 5.1: Summary of label fields.

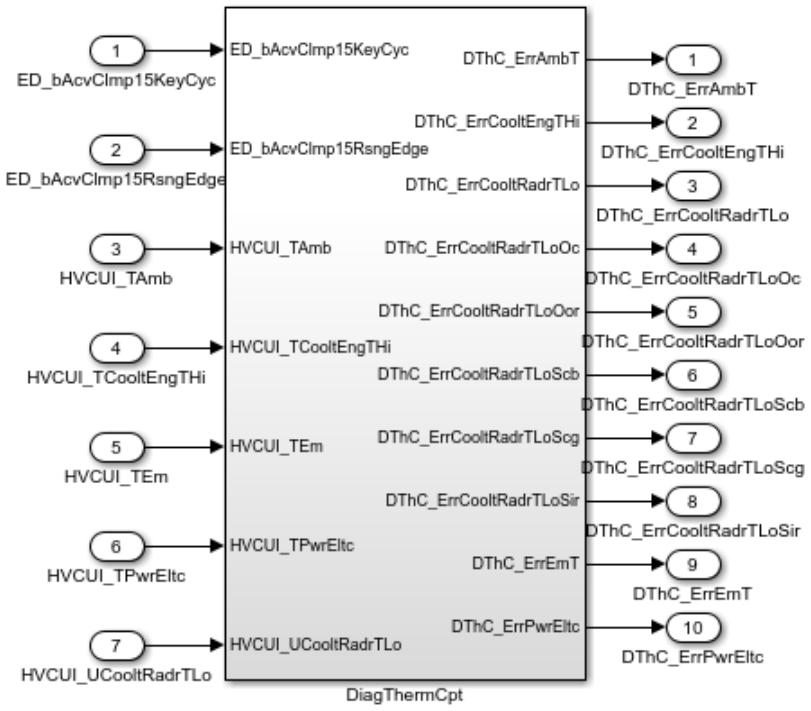


Figure 5.8: An example model subsystem in the topmost layer of the delivered model with the I/O ports.

In addition, the model parameters/signals in the data files are converted from the *AVLmpt*[4] package to the native Simulink *mpt*[5] package during the delivery process. A 'package' is specific to MATLAB/Simulink environment and can contain multiple class definitions with various storage-class attributes to qualify the model parameters and signals [43, 44]. The storage-class attributes

[4] *AVLmpt* defines various storage-class specifiers for signals/parameters handled within the Maestra framework.
[5] *mpt* package is used to qualify signals and parameters in the Simulink environment.

gain importance only in the code generation and determine how a particular signal/parameter must be handled in the generated code [43]. For example, a parameter can be qualified to be handled as a calibration parameter or as a system constant in the generated code. The Simulink *mpt* is the default package used for the models in the Simulink environment. The *AVLmpt* package is defined by AVL for the HCU software models developed within the Maestra environment. When the models are removed from the Maestra framework, the reference to the *AVLmpt* package is also lost.

5.1.4 Applying AUTOSAR Conversion

As the models have been extracted from the Maestra framework, the model conversion to AUTOSAR can be applied in the next step. The script *PrepareAUTOSARDelivery.m* was developed for applying AUTOSAR conversion to models and to generate code in AUTOSAR format. The AUTOSAR preparation for AVL software models has been handled in the Embedded Coder environment based on [45]. The general flow of the script *PrepareAUTOSARDelivery.m* is shown in Figure 5.9.

Code and Explanation

The delivery folder path, where the models and the artifacts extracted from the Maestra framework are stored, is provided as an argument to the MATLAB function call *PrepareAUTOSARDelivery.m*. The script flow can be explained in the following steps, in accordance with Figure 5.9.

1. The delivery folder contains the SWC models and the corresponding libraries delivered from the previous model extraction step. Each model library contains the SWC model implementation. In Step 1, the list of all the SWCs available in the delivery folder is prepared (Line 2 of Listing 5.12). The script then loops through the list and prepares a new model file *<Model>_AR.slx* (Line 5 of Listing 5.12) for each SWC item in the list by creating a copy of the model implementation from the corresponding model library. The MATLAB functions shown in Lines 8 to 11 of Listing 5.12 have been used to add the subsystem block and establish connections among the ports.

Listing 5.12: PrepareAUTOSARDelivery.m - Preparation of SWC list and <Model>_AR file.

```
1  % Collection of the list of model libraries
2  SWCListRaw = subdir([PrepASDelCfg.ProjectPath '\*_Lib.slx']);
3  [...]
4  %Preparation of new model file <Model>_AR
5  copyfile(SWCMainMdlPath, SWCAUTOSARMdlPath);
6  [...]
7  %Addition of model implementation in <Model>_AR from the model library
8  add_block(SWCLibPath,SubSysPath);
9  SubSysPos = get_param(SubSysPath,'Position');
10 ConnectInPrts(SubSysPath);
11 ConnectOutPrts(SubSysPath);
12 [...]
```

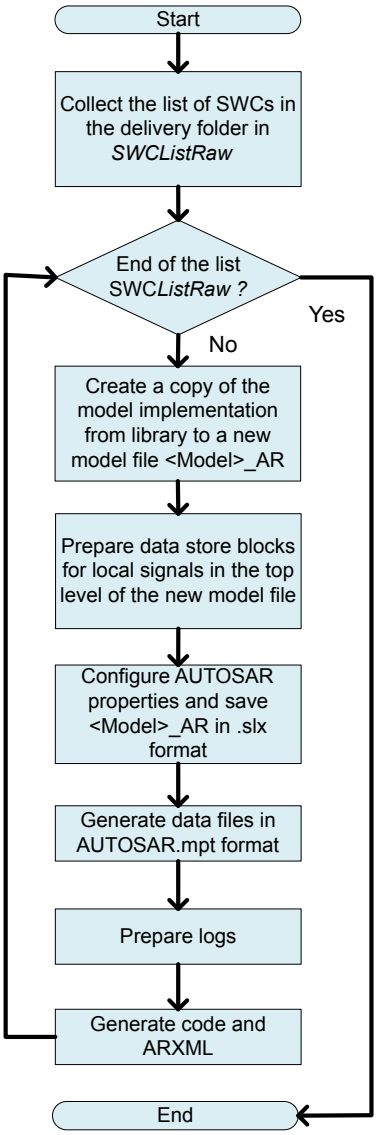


Figure 5.9: Program flow - PrepareAUTOSARDelivery.m.

Additionally, the data store memory blocks are also created in this step for handling all the local signals. The data store blocks act as internal variables to handle the local signals within the Simulink environment. A list of local signals available is collected in *DSMList* and the code excerpt from Line 3 in Listing 5.13 shows the addition of the data store memory blocks for the list of local signals contained in *DSMList*.

Listing 5.13: PrepareAUTOSARDelivery.m - Preparation of data store memory blocks.

```
% Preparation of data store memory blocks
for i=1:length(DSMList)
    hBlock = add_block('simulink/Signal Routing/Data Store ...
        Memory',[SWCAUTOSARMdlName '/' DSMList{i}]);
end
```

The above discussed part of the script *PrepareAUTOSARDelivery.m* involving the preparation of the models for AUTOSAR conversion including the data store blocks was developed by AVL for a customer project and the same concept has been used in this thesis.

2. The next step is the configuration of AUTOSAR properties for the *<Model>_AR.slx* created in the above step. In order to include AUTOSAR properties for a model, the following entities have been configured in the script:

   - **Configuration of Ports:** As the I/O communication in the AVL HCU software models involves static global variables, the Simulink I/O ports have been converted to Implicit Sender/Receiver ports.
   - **Configuration of Runnables:** The types of runnable entities configured are *Runnable_init* for initialization and *Runnable_step* (periodic runnable entity) for functional implementation. The *Runnable_step* has been renamed with the corresponding SWC model prefix.

The API commands for AUTOSAR conversion described in ([45], p.4-211) have been used for programmatically configuring the AUTOSAR properties. The model, in this case, has been configured as a default AUTOSAR component. Line 2 in Listing 5.14 indicates the MATLAB API *autosar.api.create* (Appendix D) to create a default AUTOSAR component. In Line 3 of Listing 5.14, the AUTOSAR properties of the model are extracted to a MATLAB object *autosarProps*, which can later be used to edit the runnable or port properties of the model. The runnable namings for *Runnable_init* (Lines 7 to 8) and *Runnable_step* (Lines 11 to 12) have been configured using *autosarProps* as shown in Listing 5.14.

Listing 5.14: PrepareAUTOSARDelivery.m - Configuration of AUTOSAR properties.

```
%% Configuring default AUTOSAR properties
autosar.api.create(SWCAUTOSARMdlName,'default');
autosarProps = autosar.api.getAUTOSARProperties(SWCAUTOSARMdlName);

%% Configure runnable namings
%%Init Runnable
set(autosarProps,runnables{1},'symbol',PortFormatFound_Init{1});
set(autosarProps,runnables{1},'Name',PortFormatFound_Init{1});

%%Step runnable
set(autosarProps,runnables{2},'symbol',PortFormatFound_Schedule{1});
set(autosarProps,runnables{2},'Name',PortFormatFound_Schedule{1});
```

3. In step 3, the signals and parameters data objects in the delivered data files have been converted from the native Simulink *mpt* to the *AUTOSAR* package [45]. The *AUTOSAR* package has been defined in MATLAB in order to handle the signals and parameters for AUTOSAR model development in the Simulink environment. The *AUTOSAR* package has its own set of custom storage class attributes to qualify the parameters and signals for AUTOSAR format code generation. The parameters, for example, can be set to act as local calibration parameters, global calibration parameters, or as system constants in the generated code depending on the *CustomStorageClass* setting. Table 5.2 summarizes various *CustomStorageClass* settings defined by *AUTOSAR* package and have been used in the script for various parameters and signal types.

Parameter Types	***CustomStorageClass* Setting**
Local calibration parameters	*CustomStorageClass* = 'InternalCalPrm'
Global calibration parameters	*CustomStorageClass* = 'CalPrm'
System constants	*CustomStorageClass* = 'SystemConstant'
Local signals	*CustomStorageClass* = 'perInstanceMemory'
Signals requiring NVRAM access	*CustomStorageClass* = 'perInstanceMemory' *CustomAttributes.needsNVRAMAccess* = True

Table 5.2: Various *CustomStorageClass* setting for *AUTOSAR* class package.

The part of the script *PrepareAUTOSARDelivery.m* involving the conversion of model parameters to AUTOSAR package was developed by AVL for a customer project and the same has been used in this thesis.

4. As there were only limited number of signals requiring NVRAM access in the HCU software system, these signals have been configured manually from the MATLAB workspace by setting the *CustomStorageClass* to 'PerInstanceMemory' and selecting the option *needsNVRAMAccess* to 'True' (Table 5.2) before the code generation.

5. Once the AUTOSAR features have been set-up for the model, the model C code in AUTOSAR format can be generated by Embedded Coder. To do so, a set of code generation settings has been configured in the script for the Embedded Coder environment as shown in Listing 5.15.

Listing 5.15: PrepareAUTOSARDelivery.m - AUTOSAR format code generation setting.

```
1 %% Set code generation setting
2 cs = getActiveConfigSet(SWCAUTOSARMdlName);
3 switchTarget(cs,'autosar.tlc',[]);
4 % Start code generation
5 rtwbuild(SWCAUTOSARMdlName);
```

Line 3 of Listing 5.15 indicates that the Target Language Compiler (TLC) [46] setting has been set to AUTOSAR target to generate the AUTOSAR format code and the model ARXML files. The TLC setting is native to Embedded Coder environment to customize the code generation options. Once the AUTOSAR target has been set-up, the code generation in the Embedded Coder environment can be carried out using MATLAB command *rtwbuild(Model_name)* as indicated in Line 5 of Listing 5.15. Additionally, the logs are also generated as .xlsx files, in case the code generation is affected by build errors.

Results

The results observed following the AUTOSAR conversion of the models are presented as follows. At the model level, the normal Simulink I/O ports are changed to AUTOSAR Sender/Receiver ports. The Simulink window does not differentiate the appearances of the normal port type block and the AUTOSAR port type block. Hence an image illustration of the model subsystem block has been used in Figure 5.10 for comparing the port types before and after the conversion. Figure 5.10A illustrates a subsystem block of an unconverted model with normal Simulink I/O ports (marked 'green'), and Figure 5.10B represents the subsystem block of a converted model with AUTOSAR Sender/Receiver ports (marked 'blue'). Additionally, the data store memory blocks were also fitted for the local signals (can be observed in the Simulink window) in the top level of the converted models.

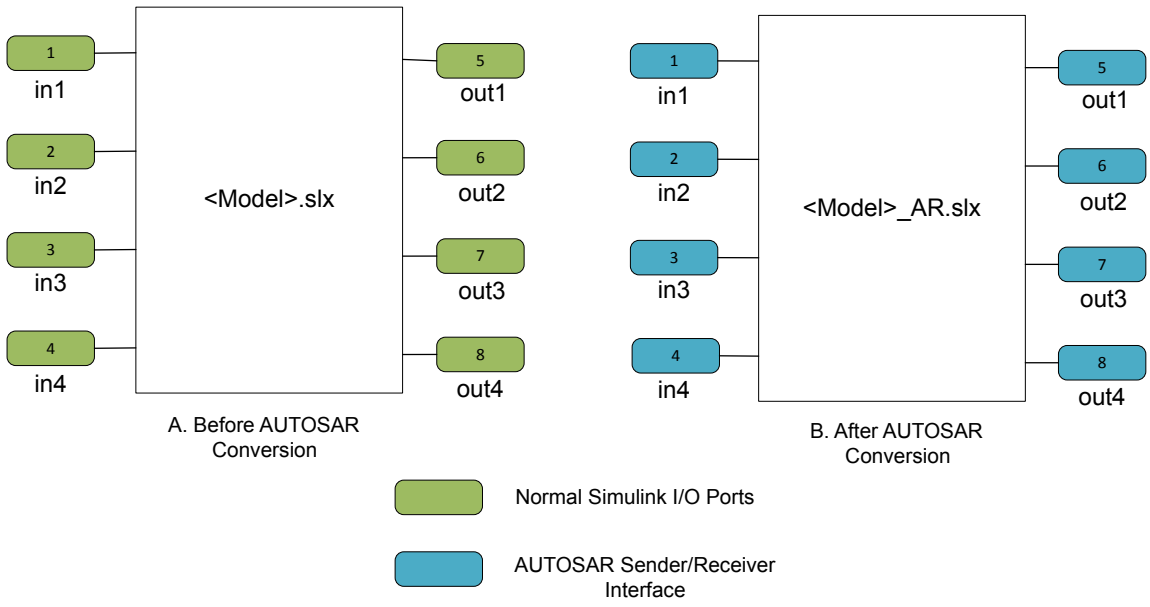


Figure 5.10: Changes at the model subsystem level before and after the AUTOSAR conversion.

The difference in the port type configuration mentioned above is reflected only in the generated code. At the code level, the AUTOSAR format code uses RTE function calls to access signals

(configured as AUTOSAR Sender/Receiver ports) and parameters in contrast to the non-AUTOSAR implementation, which uses direct variable access for signals (configured as Simulink I/O ports) and parameters. An example is shown in Listings 5.16 and 5.17, which compares a line of the code generated from an SWC model <*Model*> before and after AUTOSAR conversion. Line 2 of Listing 5.16 shows that the parameter *HVCUI_StErrBusHybCan* is accessed via direct variable access.

Listing 5.16: <Model>.c - An excerpt of code generated from unconverted model SWC.

```
1 /*CanComDiag.c*/
2 SCCD157_Logical_Operator1 = (HVCUI_StErrBusHybCan != STERRCANMSG_BUSOFF);
```

On the contrary, the same parameter *HVCUI_StErrBusHybCan* is accessed by RTE function call in the code generated from the AUTOSAR converted model <*Model*>*_AR* (Line 2 of Listing 5.17).

Listing 5.17: <Model>_AR.c - An excerpt of code generated from AUTOSAR converted model SWC.

```
1 /*CanComDiag_AR.c*/
2 CanComDiag_AR_B.RelationalOperator1_hd = ...
      (Rte_IRead_CCD_10ms_HVCUI_StErrBusHybCan_HVCUI_StErrBusHybCan() != ...
      ((uint8_T)Rte_SysCon_STERRCANMSG_BUSOFF));
```

Additionally, the parameters which have been defined as global calibration parameters have been recorded in the generated model .ARXML file as parameter interfaces in a Parameter SWC instance called *HybridGlobal*. An excerpt from the model .ARXML is shown in Listing 5.18. Line 4 in Listing 5.18 refers to the name of the Parameter SWC instance, and Line 7 indicates the parameter written to the Parameter SWC.

Listing 5.18: Parameter SWC instance in model .ARXML file.

```
1 <SHORT-NAME>HybridGlobal_AR_pkg</SHORT-NAME>
2  <ELEMENTS>
3    <PARAMETER-SW-COMPONENT-TYPE UUID="357c539a-2fc0-5dcb-0ce3-7c0bedcae973">
4         <SHORT-NAME>HybridGlobal_AR_swc</SHORT-NAME>
5             <PORTS>
6               <P-PORT-PROTOTYPE UUID="a4efdeef-5ed3-57c8-fe47-fcb81635444d">
7                  <SHORT-NAME>HybGlb_NEmActForMapEff_A</SHORT-NAME>
```

5.2 RTE Generation

This section explains the process of RTE generation for integration with the BSW. As per the proposed conversion concept in Figure 4.1, the RTE, in this case, refers to the RTE function definition involving ASW communication and parameter access. As the ASW models of AVL HCU software have been converted to AUTOSAR format and code has been generated from the previous steps, the

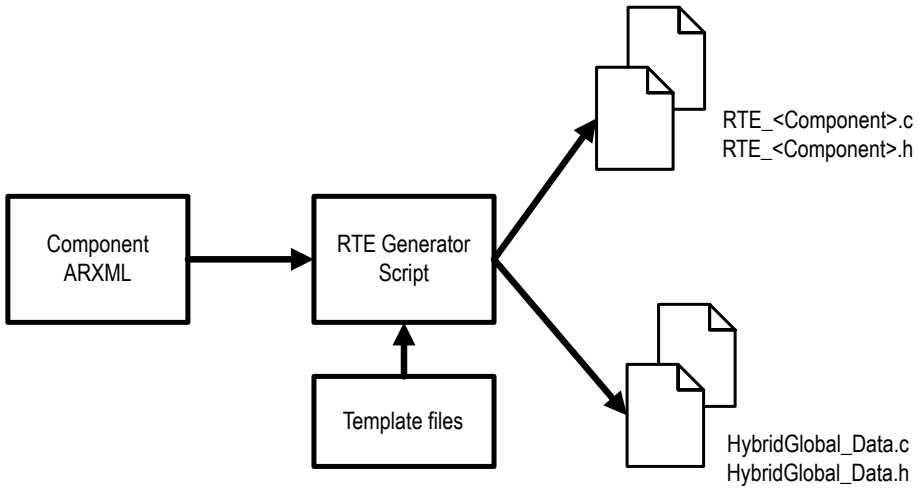


Figure 5.11: Structure of RTE generator.

next step is to generate the RTE portion. In this thesis, the RTE generation has been handled via RTE generator implemented using MATLAB. The following section explains the implementation of RTE generator.

5.2.1 Implementation of RTE Generator

A design of RTE generator has already been proposed by Shiquan Piao et al. in [7]. According to this work, an RTE generator shall contain an **ARXML parser**, which reads the contents of AUTOSAR ARXML files; a **generator engine**, which generates the code based on template and data obtained from the ARXML and; a **template** file, which describes a code structure to be used by the generator engine. The aforementioned model of RTE generator has been adopted for this thesis and structured as shown in Figure 5.11. Additionally, the RTE generator has been implemented using MATLAB M-Script and used to generate the RTE and HybridGlobal container code files as per Figure 5.11. The HybridGlobal container code files are generated as Parameter SWC instance and denote the global calibration and measurement variables[6] to be used by all the models in the HCU software system.

A general process flow of the RTE generator script *RTEGenerator.m* is shown in Figure 5.12. The implementation is explained as follows.

Code and Explanation

1. In the first step (from Figure 5.12), the template files are read by the *RTEGenerator.m*. As mentioned before, the template files provide a general structure for the RTE code text. A separate template file has been created as a text-file for Rte_<Component>.c, Rte_<Component>.h,

[6]The calibration parameters include single parameter values, 1D curve arrays and 2D map arrays.

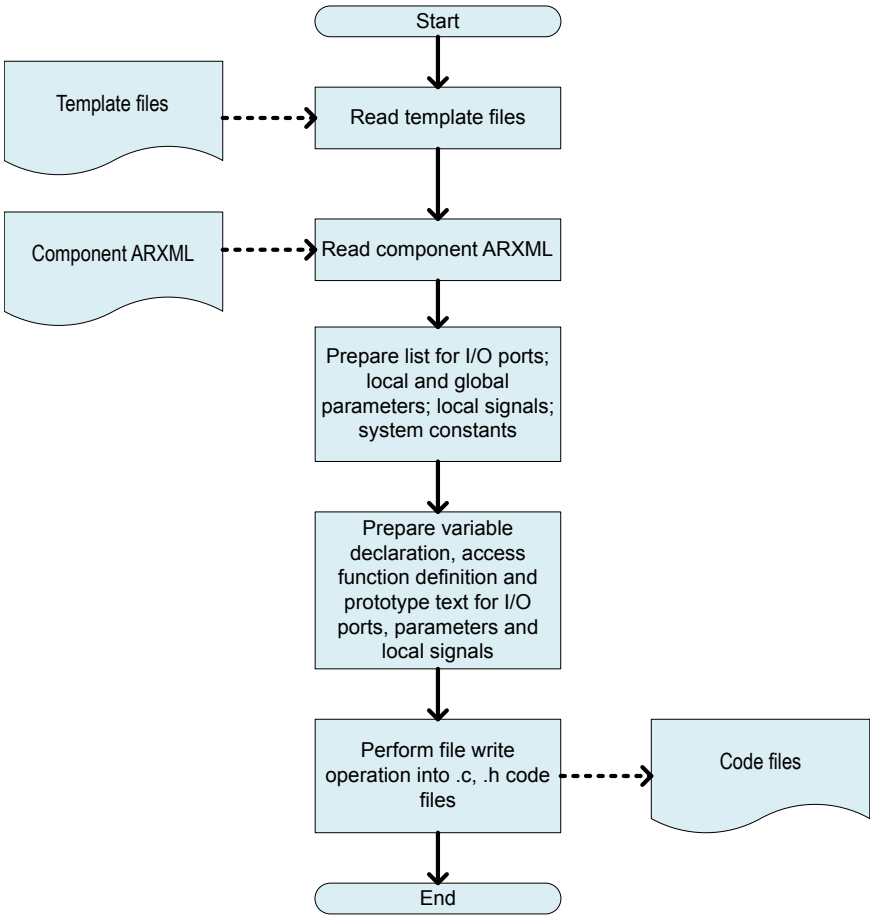


Figure 5.12: RTEGenerator.m - Process flow.

HybridGlobal_Data.c and HybridGlobal_Data.h. The template structure used for Rte_<Component>.c is shown in Listing 5.19 as an example. The template text is replaced by code text in the generated RTE files.

Listing 5.19: RTE code template.

```
1  ##HEADER INCLUDE##
2
3  ##CAL START SEC##
4
5  ##PARAMETER DECLARATION##
6
7  ##CAL STOP SEC##
8
9  ##VAR START SEC##
10
```

```
11 ##SIGNAL VARIABLE DECLARATION##
12
13 ##OUTPORT VARIABLE DECLARATION##
14
15 ##VAR STOP SEC##
16
17 ##CODE START SEC##
18
19 ##PARAMETER ACCESS FUNCTION DEFINITION##
20
21 ##READ FUNCTION DEFINITION##
22
23 ##WRITE FUNCTION DEFINITION##
24
25 ##SIGNAL FUNCTION DEFINITION##
26
27 ##CODE STOP SEC##
```

2. In Step 2, the component ARXML files are read and the parsing of ARXML takes place. The information about an SWC including the port variables, calibration parameters, system constants, and signals are collected and prepared as lists. Listing 5.20 denotes the MATLAB APIs ([45], p. 6-63) used for parsing of component ARXML. Line 2 in Listing 5.20 shows the import of component ARXML using API *arxml.import* (Appendix E). Additionally, the *find* (Appendix F) API has been used (shown in Lines 5,8,11 and 14 of Listing 5.20) to extract information, such as the Application SWCs, Parameter SWCs, system constants and signal list present in the component ARXML.

Listing 5.20: RTEGenerator.m - Parsing of ARXML and collection of SWC entities.

```
1  %% Import of ARXML components
2   ar = arxml.importer(file)
3
4  %% Application software component search
5  aswcPath = find(ar,[],'AtomicComponent','PathType','FullyQualified');
6
7  %% Get all system constant paths
8  SysConsList = find(ar,[],'SystemConst','PathType','FullyQualified');
9
10 %% Local Signals
11 signal_list = find(ar,[],'ExclusiveArea','PathType','FullyQualified')
12
13 %% Parameter software component search
14 paramcomp = ...
       find(ar,[],'ParameterComponent','PathType','FullyQualified');
```

3. Once the list of port variables and parameters have been collected, the next step is to prepare the code text. The MATLAB API *sprintf()*[7] has been used to create the code text, which involves preparing the function definitions, prototypes, and variable declarations. The data type and values of the parameters/variables are resolved from the corresponding component data files. An example of code text creation for RTE write functions *Rte_IWrite_XXX()* is shown in Listing 5.21.

Listing 5.21: RTEGenerator.m - Preparation of code text.

```
1 %% Write Function Definition
2 write_function_line  = sprintf('void Rte_IWrite_%s_%s_%s(%s ...
      data)\r\n',runnable_step_name,sportname,sportname,datatype_outport);
3 write_function_line  = sprintf('%s{\r\n',write_function_line);
4 write_function_line  = sprintf('%s %s = ...
      data;\r\n',write_function_line, sportname);
5 write_function_line  = sprintf('%s}\r\n', write_function_line);
6 outport_func_def_text = sprintf('%s%s\r\n', outport_func_def_text, ...
      write_function_line);
```

4. In the final step, the template text is converted into the corresponding code text and written to *.c, *.h files. The MATLAB file-create and file-write functions *fopen* and *fprintf* have been used in this case, as shown in Lines 2 and 3 of Listing 5.22. This step eventually generates the required files shown in Figure 5.11.

Listing 5.22: RTEGenerator.m - Code file creation.

```
1 %RTE Source file creation
2 RTE_c = fopen(code_file_name,'w');
3 fprintf(RTE_c,'%s\r\n',RTE_code_text);
4 fclose(RTE_c);
```

Results

The code files Rte_<Component>.c, Rte_<Component>.h, HybridGlobal_Data.c, and HybridGlobal_Data.h were generated as a result. Excerpts from an RTE code file *Rte_CTCa.c* generated for an Application SWC *CluTqCalc* are discussed for illustration in Listings 5.23 and 5.24. The *Rte_CTCa.c* is generated based on the RTE code template file shown in Listing 5.19.

[7]The function sprintf() is used to store data as strings. The format of usage can be found in MATLAB Help Documentation.

Listing 5.23: Rte_CTCa.c - Parameters and output variable declaration text.

```
1  #include "Rte_CTCa.h"
2  #include "Rte_HWCAC.h"
3  #include "HybridGlobal_Data.h"
4
5  #define CTC_START_SEC_CALIB_UNSPECIFIED
6  #include "CTC_MemMap.h"
7
8  /* Parameter Declaration */
9  const volatile float32 ClTC_ArClu0Pist_P = 5531.000000;
10 [...]
11
12 #define CTC_STOP_SEC_CALIB_UNSPECIFIED
13 #include "CTC_MemMap.h"
14
15 #define CTC_START_SEC_VAR_UNSPECIFIED
16 #include "CTC_MemMap.h"
17
18 /* signal Variable Declaration */
19
20 /* Output Variable Declaration */
21 uint8 ClTC_StClu0Act;
22 float32 ClTC_TqClu0CActEstimd;
23 [...]
24
25 #define CTC_STOP_SEC_VAR_UNSPECIFIED
26 #include "CTC_MemMap.h"
27 [...]
```

Lines 8 and 9 of Listing 5.23 indicate the parameter variable declaration text generated from the corresponding template text "##PARAMETER DECLARATION##" (Line 3 of Listing 5.19). The same can be shown for the output variable declaration text (Lines 20 to 22 in Listing 5.23) generated from its template text in Line 13 of Listing 5.19. In the generated RTE code files, the variable types are also associated with their corresponding memory mapping keywords in the code text (shown in Lines 5 and 15 of Listing 5.23).

Listing 5.24: Rte_CTCa.c - Parameter access function and write function definition text.

```
1  [...]
2  #define CTC_START_SEC_CODE_UNSPECIFIED
3  #include "CTC_MemMap.h"
4
5  /* Parameter Access Function Definition */
6  float32 Rte_CData_ClTC_ArClu0Pist_P(void)
7  {
8   return ClTC_ArClu0Pist_P;
9  }
10 [...]
11
12 /* Read Function Definition */
```

```
13 boolean ...
       Rte_IRead_ClTC_10ms_SF_StClu0FillgCmplActFb_SF_StClu0FillgCmplActFb(void)
14 {
15 return SF_StClu0FillgCmplActFb;
16 }
17 [...]
18
19 /* Write Function Definition */
20 void Rte_IWrite_ClTC_10ms_ClTC_StClu0Act_ClTC_StClu0Act(uint8 data)
21 {
22   ClTC_StClu0Act = data;
23 }
24 [...]
25
26 /* signal Access Function Definition */
27
28 #define CTC_STOP_SEC_CODE_UNSPECIFIED
29 #include "CTC_MemMap.h"
```

Similarly, Listing 5.24 shows the function definitions generated for I/O read/write and parameter access based on their template text in Listing 5.19. For example, the template text "##PARAMETER ACCESS FUNCTION DEFINITION##" (Line 19 of Listing 5.19) has been filled with the parameter access function definition in Listing 5.24 (Lines 6 to 9). The variable declaration and function definition text for the local signals (shown in Line 18 of Listing 5.23 and Line 26 of 5.24) is filled with empty spaces, which means that the SWC model *CluTqCalc* does not use any local signals and the signal list is empty. Additionally, in the generated RTE code files, the standard data types of variables and function declaration have been adopted according to the AUTOSAR platform types described in [47].

5.3 Integration

This section discusses the integration and build process. As per the AUTOSAR conversion concept proposed in Section 4.2, the pre-configured BSW of the AVL HCU software along with the CIL layer has been reused for integration. Therefore, the configuration of BSW modules using specific configuration tools, as specified in the AUTOSAR methodology, is not required in this case. In the build process of the AUTOSAR converted software, the generated AUTOSAR format ASW code files, along with the RTE, CIL and the BSW files, are compiled in a build environment. The same build environment involving Hightec compiler suite, which is used for the original AVL HCU software, has been used here for building the AUTOSAR converted software. The result of the build process is the ECU executable in *.hex* format which can be flashed in the HCU hardware. For the system build performed after the generation of all the code files, no additional modifications were required in the code level to suit the compiler requirements. Infineon Aurix 32-bit TC275 [48] was the microcontroller platform used in the HCU hardware.

The build environment makes use of a customized *make* file with batch options in order to invoke the build process as a batch run from the Windows command prompt. The build process can

be explained in the following steps. In the first step, the ASW codes are compiled and the corresponding object files are generated. The next step involves the generation of the A2L file. The A2L is a description file format defined by the ASAM[8] standards in order to translate the memory addresses of the calibration and measurement variables into a format accessible via the software tools for calibration [49]. In order to generate the A2L file, Data Declaration System (DDS) [50] software tool has been used. The SWC *.ddx* files are read as input in the DDS and are converted into a single A2L file for the HCU software system. Once the A2L file is generated, in the final step, the compiled ASW object files are linked with the BSW object files and exported as a single executable in *.hex* format.

Results

As a result of the build process, the following list of files were generated (Figure 5.13):

- An A2L file for calibration access.
- An executable in *.elf* format which contains the debug information [51]. This format is used for debugging the software using a debug tool[9].
- An executable in *.hex* format which is a binary file flashable in the ECU hardware.
- A linker map file that provides the memory mapping information.

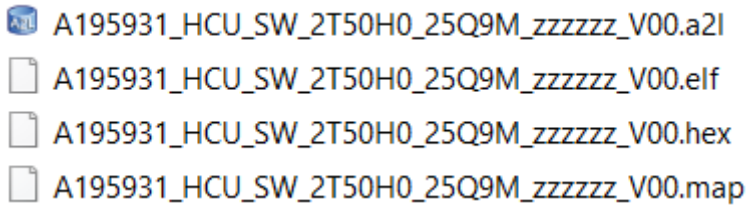


Figure 5.13: Output files generated from the build process of AUTOSAR converted software.

In addition, the executables were also generated for four different versions of AUTOSAR converted software with different optimization settings for memory and run-time efficiency. These optimization options include making the RTE function calls *inline* in the code or setting different compiler optimization flags (from O0 to O3) during compilation. The *inline* keyword is an indication to the compiler to insert the function code in the place of function calls, thereby reducing the calling and return overheads [53]. The compiler introduces additional code optimizations during compilation with different optimization flags, thus improving the "code size and execution time" [54, 55]. The different flag options (O0 and O1) have been adjusted under the compiler settings in the *make* file.

[8] Association of Standardization of Automation and Measuring Systems.
[9] Universal Debug Engine (UDE) [52] is the debugger currently being in use at AVL.

It must also be noted that only the optimization levels O0 and O1 have been used in the AUTOSAR converted software, since introducing higher optimization levels can affect the functionality of the software[10]. The different versions of AUTOSAR converted software created by varying different optimization settings are shown as follows:

- **AUTOSAR Normal Version** with no optimization settings. The optimization flag is O0 in this case, which is the default setting in the compilation and indicates that zero optimization has been introduced.
- **AUTOSAR Inline Version** [11] wherein all the RTE function definitions have been made *inline*. The optimization level is O0 for this software version.
- **AUTOSAR Optimized Version Level 1** which has been compiled with compiler optimization flag set as O1. The RTE function calls are not *inline* in this software version.
- **AUTOSAR Optimized Version Level 2** in which all the RTE function definitions have been made *inline* as well as the compiler optimization flag O1 has been set during compilation.

The different versions of AUTOSAR software thus generated are subjected to KPI metrics evaluation with the non-AUTOSAR AVL HCU software used as a reference.

[10] AVL uses only O0 or O1 in their original HCU software for ensuring proper software functionality and the same has been adopted in this thesis for the AUTOSAR converted software. It has been understood that higher optimization levels can introduce excessive round-off errors in floating point arithmetic calculations which can adversely affect the software functionality.

[11] The RTE functions definitions for AUTOSAR Inline Version were modified manually from the AUTOSAR Normal Version and the RTE generator script was not used in this case.

6. Evaluation

This chapter discusses the testing and evaluation of the different AUTOSAR software versions in comparison to the reference non-AUTOSAR HCU software. For the different AUTOSAR software versions, the functionality and performance were analyzed on a HIL setup. Subsequently, KPI metrics such as memory consumption, task runtime, stack usage, and CPU utilization were also evaluated.

6.1 Experimental Setup

National Instruments VeriStand [56], a real-time simulation environment with hardware and software, is the customized setup used by AVL for HIL simulation. The software of the VeriStand system is a Linux based environment and can be programmed to simulate a particular behaviour. The VeriStand system, in this case, was loaded with a plant model simulating the vehicle behaviour. Figure 6.1 shows that the HCU serves as the Device Under Test (DUT) and is connected in closed loop mode with the simulation environment. This type of set-up is an effective way to verify the behaviour of HCU in a simulated vehicle system. Each software version (both reference non-AUTOSAR and AUTOSAR software versions) to be evaluated for KPI metrics was flashed in the HCU hardware individually and the behaviour in the HIL environment was analyzed.

In order to ensure proper functionality of each software, a set of functional tests were performed. Firstly, the behaviour of the software versions during the HCU power-on cycle was monitored. Secondly, a simple I/O functionality test was performed, which involved passing a random input signal from the HIL simulation environment and observing the corresponding output from the HCU. In this phase, the correct transmission of the required CAN messages in the bus lines was also checked. Thirdly, a simulation of the New European Driving Cycle (NEDC) [57] was carried out in the HIL environment. In real vehicles, the NEDC is an on-road velocity profile test performed to measure the emission levels. The NEDC test profile was employed since it involves a more comprehensive check on the software functionality by varying multiple inter-dependent parameters such as velocity, engine Rotation Per Minute (RPM) and transmission, etc.

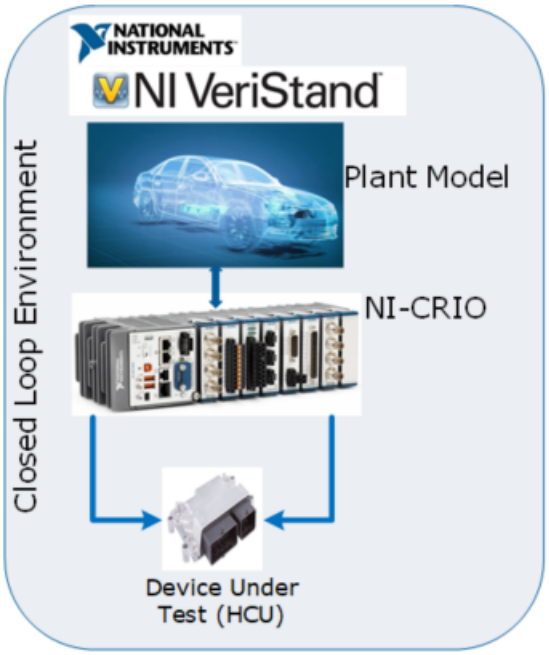


Figure 6.1: HIL test environment for evaluation.

6.1.1 Observations

All the software versions (both AUTOSAR and non-AUTOSAR versions) passed the power cycle test. The voltage and current levels of the HCU during the power-on phase were well within the permissible levels (HCU voltage level: 12-13V; HCU current level: 0.7-0.8A). The transmission of CAN signals in the network was also observed for all the software versions when the ignition was set to *RUN* state. Additionally, all the software versions passed the I/O functionality test, wherein, for some simulated input signals, the transmission of corresponding output CAN signal was observed in the network. The above observations ensured that the software functionality in terms of OS task execution and runnable entity scheduling was proper in all the software versions. The AUTOSAR software versions, however, did not pass the simulated NEDC test, while the original AVL HCU software was successful in the NEDC run. The root cause of the failure was found to be the improper functionality of some of the look-up table mappings in the code generated from Embedded Coder[1]. However, owing to time constraints, the issue with look-up table mappings could not be resolved for the AUTOSAR software versions and the evaluation was limited to the analysis of KPIs such as task runtime, stack usage, and CPU utilization. The signals pertaining to the above metrics were recorded for about 300 seconds using the Vector CANape [58] environment.

[1] A similar issue could not be observed in the TargetLink generated code of the original AVL HCU software.

6.2 Memory Consumption Analysis

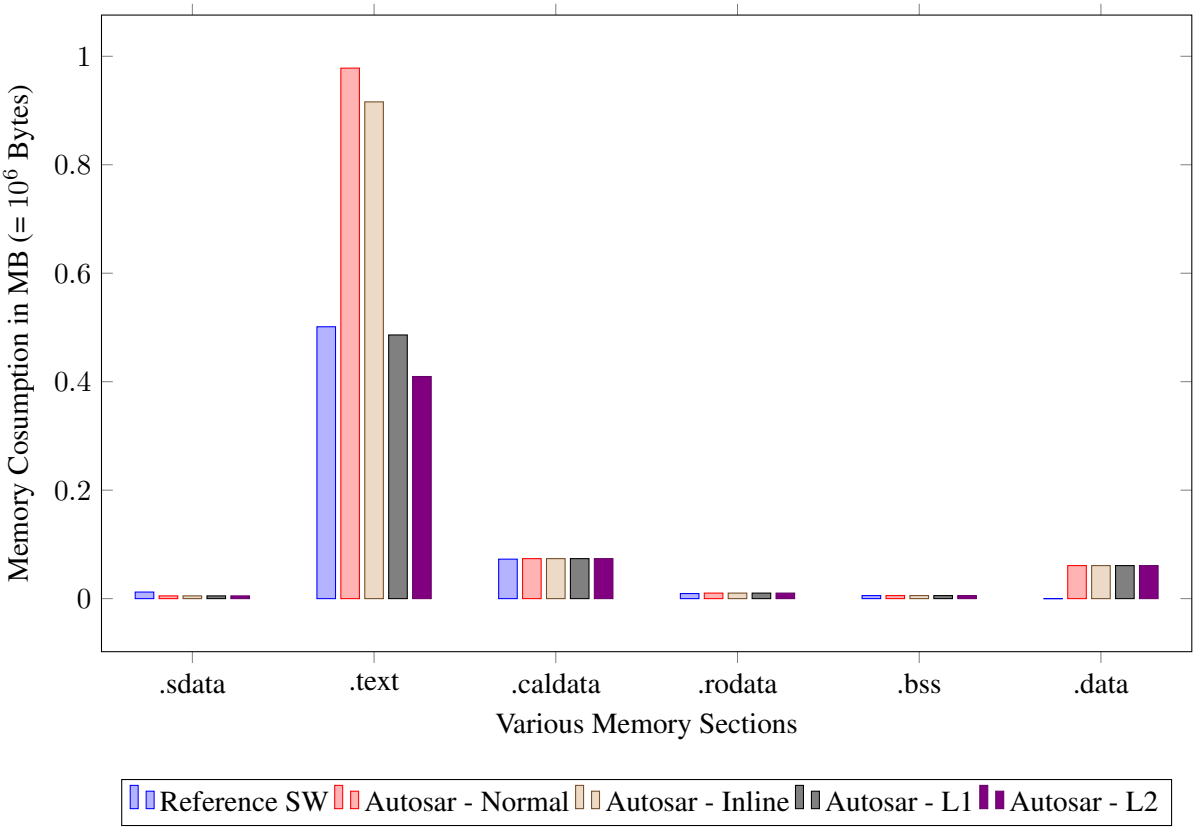


Figure 6.2: Analysis of memory consumption.

This section compares the memory consumption of the ASW codes for the AVL HCU software and the different AUTOSAR software versions. The memory consumption result was generated out of the build process by a Python script, which calculates the total utilization per various memory sections by analyzing the ASW compiled object files. The description of various memory sections to be analyzed are as follows:

- **.sdata** and **.data** are used to store initialized static global variables. Unlike the .data section, the memory size allocated to the .sdata section is comparatively limited.
- **.text** section contains the code portion.
- **.caldata** section stores the volatile calibration and measurement variables.
- **.bss** section holds the uninitialized global variables.

Table 6.1 lists the memory usage in bytes associated with different memory sections for all the software versions (both reference non-AUTOSAR and AUTOSAR versions). Each numeric data

	.sdata	.text	.caldata	.rodata	.bss	.data	TOTAL
Reference SW	12 129	501 290	72 799	9 356	5 631	19	601 224
AUTOSAR - Normal	5 071	978 152	73 760	10 214	5 631	60 910	1 133 738
AUTOSAR - Inline	5 071	915 924	73 760	10 214	5 631	60 910	1 071 510
AUTOSAR - Optimized Version L1	5 071	486 154	73 760	10 214	5 631	60 902	641 732
AUTOSAR - Optimized Version L2	5 071	409 564	73 760	10 214	5 631	60 902	565 114

Table 6.1: Summary of memory utilization in bytes.

per cell in Table 6.1 from Columns 2 to 7 represents the section-wise total memory consumption of the SWCs in the HCU software system. The data in Column 8 of Table 6.1 represents the aggregate memory consumption over all the memory sections. Figure 6.2 alternatively shows a comparative study of the memory consumption in the form of a bar diagram.

From Figure 6.2, it can be noted that the trend of memory consumption is relatively uniform in .caldata, .rodata and .bss sections, while contrasting differences can be observed in .text and .data (or .sdata) portions for the non-AUTOSAR and AUTOSAR software versions. Overall, the AUTOSAR software versions tended to occupy more byte words than the non-AUTOSAR HCU software, unless a higher degree of optimization is applied for the AUTOSAR versions.

For the initialized global variables, the memory consumption in the .data section for the AUTOSAR versions is compared with that of the .sdata section for the reference software (Figure 6.2). The reason is that the .data section was used for storing the initialized variables in the AUTOSAR versions due to increased memory requirements, while the .sdata section was used in the case of reference software. The total memory consumption is higher by nearly six-fold for the AUTOSAR versions when compared with the reference software. The stark increase in the memory consumption for the AUTOSAR versions can be due to the creation of local variables in the code generated by Embedded Coder for each operation involving a Simulink block. A separate structure definition with the block variables is created for each SWC of the HCU software system, making up for huge consumption in the .data section for the AUTOSAR software versions. The above statement was verified from the linker map file (shown in Figure 5.13) generated for the AUTOSAR software versions. Conversely, in the code generated by TargetLink for the reference AVL HCU software, a majority of the TargetLink block operations are combined in a single code statement and only fewer local variables are created, which in turn does not cause a huge demand in the memory requirements.

In the .text section, there is an increase of nearly two-fold in the memory consumption for the AUTOSAR Normal and Inline versions (optimization level O0) when compared with that of the reference software (Figure 6.2). The RTE function definitions contribute to the part of the increase in the code size. Additionally, the SWC code generated from Embedded Coder (for the AUTOSAR

versions) tends to occupy more memory space than its counterpart TargetLink generated code (for the reference software), possibly due to the difference in code structure generated from different generator tools. Nevertheless, when O1 optimization has been set as in the AUTOSAR Optimized version, the compiler introduces additional optimization techniques, which in turn reduce the code size significantly.

6.3 Task Runtime Analysis

As per Sections 3.3.3 and 4.2, only one 10ms task is used to invoke the ASW runnable entities in both non-AUTOSAR and AUTOSAR software versions. This section compares the runtime metric of the 10ms task for the non-AUTOSAR reference software and the AUTOSAR software versions. The task runtime is calculated in the simulation environment by computing the differences in the time stamps between the entry and exit points in the task body. The signal pertaining to task runtime calculation has been recorded for about 300 seconds (30000 task runs with the periodicity being 10ms) for all the software versions and the average runtime values computed for each software version are shown in Table 6.2.

	Average Task Runtime (ms)	**Percentage Change**
Reference SW	2.423	0
AUTOSAR SW - Normal	6.384	+163%
AUTOSAR SW - Inline	5.347	+120%
AUTOSAR SW - Optimized Version L1	4.177	+72%
AUTOSAR SW - Optimized Version L2	2.698	+11%

Table 6.2: Percentage change in task runtime.

The variation in the average task runtime values for the AUTOSAR software versions has been analyzed by setting the average runtime value of the non-AUTOSAR software as the reference. The average task runtime in the AUTOSAR Normal version is almost three times higher than the reference value. The average task runtime is directly proportional to the ASW code size (shown in Column 3 of Table 6.1). The code size is maximum for the AUTOSAR Normal version and therefore the task runtime value peaks for this software version with a difference of about 160% from the reference value (Table 6.2). The RTE function call overheads additionally contribute to the delay in the task execution for the AUTOSAR Normal version. The task runtime, however, improves significantly with the increasing optimization levels. When the RTE function calls are made *inline* in the AUTOSAR Inline version, the function call overheads are eliminated and thus the runtime improves slightly by about 40%. When O1 level optimization has been introduced as in the AUTOSAR Optimized L1 software, a significant improvement in the average task runtime to about 4ms can be observed. The reason is the reduction in code size due to compiler induced optimizations, yet the RTE function calls are not *inline* for the L1 version. For a greater degree of optimization as in the AUTOSAR Optimized L2 software, the runtime metric is almost equal to

the reference value. In addition to the O1 optimization flag, the L2 version also includes inlined RTE functions, which improves the average task runtime potentially. Overall, the non-AUTOSAR software fared better than the AUTOSAR versions in the runtime analysis. However, a significant improvement in the performance of AUTOSAR versions could be observed with different optimization settings. In addition, a detailed analysis in the OS level, such as the variations in the kernel time and communication overheads, was not performed since the BSW supplier does not provide the required interfaces to measure these parameters.

6.4 CPU Utilization Analysis

	Average CPU Utilization (%)	**Percentage Change**
Reference SW	64.29	0
AUTOSAR SW - Normal	53.84	-16%
AUTOSAR SW - Inline	91.14	+41%
AUTOSAR SW - Optimized Version L1	80.94	+25%
AUTOSAR SW - Optimized Version L2	66.70	+3%

Table 6.3: Percentage change in CPU utilization.

CPU utilization factor is the measure of the percentage of CPU time being used for program execution in comparison with the CPU idle time. As indicated in Section 5.3, the CPU in this context refers to the Infineon Aurix 32-bit TC275. The algorithm of CPU usage calculation is implemented in the BSW by the supplier. The implementation of CPU usage calculation is however abstracted in the BSW object files delivered to AVL and the supplier provides only the signal interpreting the CPU utilization, which can be read in the Vector CANape environment. This signal measures the overall CPU usage (in percentage) by the BSW OS and not just the CPU usage factor of the 10ms task. The signal measuring the CPU usage was recorded for about 300 seconds and the average CPU usage factor observed for each software versions is tabulated in Table 6.3. Column 2 of Table 6.3 shows that average CPU usage factor observed in AUTOSAR Normal version does not correlate with the other AUTOSAR versions. The exact reason for this variation is not clearly known. However, looking at the trend of observations in the other AUTOSAR versions (Inline and Optimized) and the reference software, it has been assumed that the CPU usage factor coincides with the task runtime. More the task runtime, higher is the CPU usage factor, although the execution of CAN interrupts can also contribute to the latter. Even though the CPU usage factor of the AUTOSAR Inline version was critically just over 90%, the program execution was stable in all the cases and no situation of system overloading (CPU usage factor of 100%) had occurred, in which case, an ECU reset might have been triggered.

	Average Stack Usage(%)	Percentage Change
Reference SW	51.42	0
AUTOSAR SW - Normal	48.22	-6%
AUTOSAR SW - Inline	49.89	-3%
AUTOSAR SW - Optimized Version L1	46.56	-9%
AUTOSAR SW - Optimized Version L2	45.03	-12%

Table 6.4: Percentage change in stack usage.

6.5 Stack Usage Analysis

Stack usage factor is the percentage of stack memory used in program execution. The stack in this context refers to the user stack (of the CPU Infineon Aurix 32-bit TC275), which is used when the ASW runnable entities are executed. The size of the ASW stack memory is about 16KB. As the case with CPU usage factor, the calculation of stack usage is implemented by the BSW supplier and abstracted in the BSW object files. Additionally, only the signal interface measuring the stack usage is visible from the BSW. This signal interprets the percentage of stack occupation during ASW execution and has been recorded for about 300 seconds. Table 6.4 shows the trend in the percentage of stack memory used by different software versions. The trend in the stack usage is not uniform, although the variations are only in smaller proportions. The reason for the above deviation could not be established. However, it can be noted that the stack usage values of the all the software version are well within the critical value of 100%, more than which indicates a condition for stack overflow.

In summary, the original AVL HCU software (the reference software) performed better than the AUTOSAR versions in task runtime and memory consumption metrics. The observation is in accordance with [5], wherein Daehyun et al. mention that the incorporation of AUTOSAR concepts brings about an improvement in the performance factors such as code runtime and memory size. However, when optimizations were applied such as using *inline* keywords for RTE function calls and setting compiler optimizations, a drastic improvement in the performance factors (memory consumption and task runtime) was observed for the AUTOSAR converted software.

7. Conclusion

This chapter presents a brief outlook on the research carried out in this thesis, discusses some inferences, and provides some recommendations for further research.

7.1 Summary

The aim of this thesis was to convert the AVL HCU software towards AUTOSAR compliance and to distinctly establish an AUTOSAR software development methodology for AVL Powertrain Controls Dept. The software deviations from the AUTOSAR concepts had to be observed not only at the software architecture level but also along each and every phase of software development. Therefore, the analysis of software deviation was performed along the SDLC, namely the V-Model. A comparison was made between the AUTOSAR methodology and the AVL's methodology, and it had been thoroughly analyzed on the expectations when AVL chooses to follow AUTOSAR methodology in the future. In terms of software conversion to AUTOSAR, a concept was proposed, in which, the ASW was converted to AUTOSAR format and integrated with the BSW via the RTE layer generation. The BSW, which is not AUTOSAR compliant, had been reused, and the CIL layer had been retained. The RTE portion was generated tailoring the need for integration. The resulting software did not meet the ICC3 conformance level however, it could satisfy AUTOSAR ICC1 requirements. MATLAB scripts were additionally developed to automate the ASW conversion and the RTE generation. Out of all the MATLAB scripts used in this thesis, the delivery scripts (Section 5.1.3) were provided by AVL. Additionally, in *PrepareAUTOSARDelivery.m* (Section 5.1.4), the algorithms involving the preparation of models for AUTOSAR conversion and the conversion of model parameters and signals to the AUTOSAR package were developed by AVL for a customer project and were adopted in this thesis. In the system build, a total of four versions of AUTOSAR HCU software with different optimization techniques were prepared. These AUTOSAR software versions were validated on a HIL set up and the performance metrics such as the memory consumption, task runtime, CPU usage, and stack usage were compared with a reference non-AUTOSAR AVL HCU software.

7.2 Discussion

Although it has been said that the software is compliant with AUTOSAR, an ICC3 level AUTOSAR compliance was still not achievable due to the following factors:

- The usage of non-AUTOSAR BSW in the conversion concept to AUTOSAR.
- The presence of the CIL layer and its supplier-specific interfaces to the BSW.
- The I/O Hardware Abstraction handling (Section 3.3.2) has not been implemented as per AUTOSAR standards. This is partly due to the non-AUTOSAR BSW.
- The absence of RTE events for actuating the dynamic behaviour of ASW.

The reason here is quite obvious: The AUTOSAR methodology has not been followed from scratch of the development process. It can be inferred that it is highly unlikely to incorporate the AUTOSAR specific concepts at the granular level without following the AUTOSAR methodology completely. When an ICC3 level AUTOSAR compliance is aimed, it is imperative to use the AUTOSAR specific BSW stacks for integration with the ASW, along with the standard AUTOSAR toolchains for configuration and RTE generation. The above observation is also supported in the work by Daehyun et al. [5]. In the proposed conversion concept, the BSW has been reused since AUTOSAR specific BSW stacks were not procured for this project. The CIL has been retained since more manual modification in the code level may be required if the layer has to be removed. The AUTOSAR based I/O access mechanism using ECU Abstraction type SWC can be implemented only with AUTOSAR specific BSW stacks and has to be configured during the BSW configuration phase. In addition, the RTE events are also included in the AUTOSAR ICC3 implementation, and they have to be configured in the BSW configuration phase. These RTE events are however not part of the BSW (used in this thesis) implementation by the supplier and therefore are not used in the AUTOSAR converted software. The AUTOSAR conversion concept proposed in this thesis can meet ICC1 conformance requirements since the interfaces between the ASW and the cluster consisting of RTE, BSW, and the CIL are standardized via RTE function calls (Section 4.2). Moreover, this conversion approach cannot be adopted for all the non-AUTOSAR legacy software models. It is rather dependent on the architecture of the legacy software. In some cases, the complete ASW functionality has to be decomposed into specific AUTOSAR SWC types, as indicated by Daehyun et al. [5]. As there were about 40 non-AUTOSAR AVL HCU software models to be converted to AUTOSAR format in this work, MATLAB scripts were developed to automate the model conversion to AUTOSAR and code generation. The application SWCs thus converted to AUTOSAR format can also be deployed in an AUTOSAR system (with AUTOSAR BSW stacks). However, in this case, the RTE portion has to generated only using standard RTE generator tools. The RTE generator script used in this thesis was developed keeping in mind the conversion concept shown in Figure 4.1 and cannot substitute a standard RTE generator tool since the script generates only the RTE function definitions involving SWC communication and parameter access. The RTE generator script, however, is further modifiable and can be adapted in the future based on the structure of the RTE code needed. Furthermore, in terms of performance, the non-AUTOSAR software version fared better than the AUTOSAR

versions in execution time and memory consumption analysis. The reasons are the increase in the code size for the AUTOSAR versions and the function call overheads introduced by the RTE function calls. Daehyun et al. [5] additionally indicate that the incorporation of AUTOSAR concepts can lead to an increase in code size and execution time. Nevertheless, with several optimization techniques such as compiler induced optimizations and *inlined* function calls, it is shown that the performance of AUTOSAR versions can be significantly improved. Finally, in comparison with the current AVL software development methodology, which also involves manual implementation of the CIL, the migration to AUTOSAR methodology provides some benefits such as the elimination of manual effort necessary in coding the CIL layer. However, if AVL chooses to follow AUTOSAR methodology, additional configuration steps of the BSW modules and the RTE are also involved.

7.3 Recommendation

Based on the above discussions, further works can be carried out in one of the following areas:

- The ICC1 compliant HCU software in the next stage can be converted to a fully AUTOSAR compliant ICC3 software. The AUTOSAR converted ASW models can be integrated with AUTOSAR specific BSW stacks with the necessary configuration and RTE generation. The performance metrics of the ICC3 software can also be analyzed in comparison with the ICC1 software.
- It has been said based on theoretical concepts that an ICC1 level of AUTOSAR compliance has been achieved. Yet this compliance level is still not certified. Gilberg et al. [59] mention the AUTOSAR conformance test scenarios and the conformance certification by a third party agency. The software, in the next stage, can be subjected to conformance certification and in case any deviations detected from the standard, the conversion concept can be further improved.
- Thomas [60] mentions various optimization techniques at the BSW level to improve memory usage and runtime performances. However, these optimization techniques cannot be applied to the BSW used in the thesis since the BSW implementation is abstracted in the object files delivered to AVL. In case customizable AUTOSAR specific BSW stacks are used for integration with ASW, the effects of these optimization techniques on the software performance can be further studied. [61] and [62] further discuss other categories of optimizations that can be applied such as in the scheduling mechanism of OS tasks or in the processing of the signals transmitted via the COM module.
- Although the CPU used in this thesis (Infineon Aurix Tricore) is multi-core, only a single core is used for software execution. The multi-core support has been included from AUTOSAR 4.0, and so, the possible extension of the software towards a multi-core platform can also be investigated once the ICC3 compliance is achieved. [63] and [64] serve as good starting points, which analyze various strategies and challenges towards multi-core migration.

A. Format of Memory Mapping Keyword (AUTOSAR)

The AUTOSAR specification [31] defines a general format for the memory mapping keyword:

<COMPONENT_PREFIX>_START/STOP_SEC_<NAME>

where

- <COMPONENT_PREFIX> indicates the module abbreviation of the SWC.
- <NAME> denotes the memory section types: VAR for variables, CODE for code portion, CONST for constants and CALIB for calibration variables.

The VAR section can additionally include:

- Initialization policy <INIT_POLICY> postfix, which indicates the initialization (or cleared) status of the variables after reset or power cycle. Some of the postfixes are: INIT, NO_INIT and CLEARED.
- Variable alignment <VAR_ALIGNMENT> postfix, which indicates the size of the variables and can be denoted by one of the following postfixes: BOOLEAN, 8 bit, 16 bit, 32 bit, PTR and UNSPECIFIED.

B. Format of Memory Mapping Keyword (AVL HCU Software)

The BSW supplier of AVL HCU software defines the memory mapping keyword in the following format [12]:

ASW_OEM_START_SEC_<DEFAULT/SMALL>_<NAME>

where

- The declaration of all fast accessible variables (variables to be placed in .sdata and .sbss sections in the memory) is placed under the keyword with SMALL. The DEFAULT postfix is used for all the other types of variables and the runnable entity definitions.
- <NAME> denotes the different memory section types. The code portion is placed under the postfix CODE. The variable declarations are additionally placed with the following details:
  - Initialization policy: INIT for variables initialized to previous values after reset (or power cycle); CLEARED for variables cleared to zero.
  - Allocated size of the variables: 8, 16, 32, UNSPECIFIED.

C. tl_clear_system

Used to clear TargetLink blocks.

Syntax

[options, msg] = tl_clear_system('system', Model)

Description

Clears the TargetLink properties of the *Model*. The output variable *msg* is a structure that contains logs from deenhancement. The variable *options* is a structure that contains the options used.

D. autosar.api.create

Creates an AUTOSAR component for models developed in Simulink [45].

Syntax

autosar.api.create(Model, 'default')

Description

Creates default AUTOSAR component for *Model* with all ports configured as Implicit Send/Receive and returns AUTOSAR properties as Simulink object.

E. arxml.importer

Imports ARXML file as MATLAB objects [45].

Syntax

arProps = *arxml.importer(componentname)*

Description

Imports the ARXML with the *componentname* and returns AUTOSAR properties as Simulink object to *arProps*.

F. find

Used to find the paths of AUTOSAR entities [45].

Syntax

1. *find(arProps, [], SWCEntity, 'PathType', 'FullyQualified')*
2. *find(arProps, aswcPath{1}, PortEntity, 'PathType', 'FullyQualified')*
3. *find(arProps, paramcomp{1}, PortEntity, 'PathType', 'FullyQualified')*

Description

1. For the given AUTOSAR properties *arProps*, the function finds the paths of one of the following *AUTOEntities* and returns as MATLAB cell array:
   - AUTOEntitiy = 'AtomicComponent' for Application SWC
   - AUTOEntitity = 'ParameterComponent' for Parameter SWC
   - AUTOEntitity = 'SystemConst' for system constants
   - AUTOEntitity = 'ExclusiveArea' for local signals
2. For the given AUTOSAR properties *arProps* and *aswcPath*, the function finds the paths of one of the following *PortEntities* and returns as MATLAB cell array:
   - PortEntity = 'DataRecieverPort' for Receiver ports
   - PortEntity = 'DataSenderPort' for Sender ports
   - PortEntity = 'ParameterData' for parameters
   - PortEntity = 'Runnable' for runnable entities
3. For the given AUTOSAR properties *arProps* and *paramComp*, the function finds the paths of one of the following *PortEntities* and returns as MATLAB cell array:

- PortEntity = ’ParameterSenderPort’ for Parameter Sender ports
- PortEntity = ’ParameterReceiverPort’ for Parameter Receiver ports

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