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İÇİNDEKİLER

BÖLÜM 1

COMBINED ORGANIC RANKINE CYCLE AND VAPOR COMPRESSION REFRIGERATION SYSTEMS: A STATE OF THE ART REVIEW AND CURRENT CHALLENGES

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1.Introduction

In the case of the world's ever-increasing energy demand, the requirement for efficiency and sustainability in the energy systems is now a matter of critical interest. Traditional systems of energy production have been designed with single purposes in mind: generating either electricity or cooling. Now, because of the limited resources of energy and because of ecological sustainability issues, the development of hybrid energy systems has started. In this context, the concept of the ORC-VCR system is the coupling of an Organic Rankine Cycle with a Vapour Compression Cycle system, which becomes a novelty offering combined power generation and cooling possibilities. The systems of ORC-VCR efficiently combine power generation with cooling by the use of low-and medium-temperature sources of waste heat. Application areas of such systems are very important in situations related to the recovery of industrial waste heat, geothermal energy, solar energy, and other renewable energy sources. This chapter therefore will carry out an extensive review, starting from basic concepts of ORC-VCR systems, on thermodynamic evaluations, energy and exergy efficiencies, working fluid selection, optimization methodologies, and real-world applications.

The literature review covers an in-depth study of the most recent research concerning ORC and VCR integrated systems, within the framework set by the cited literature. Most of these studies focused on performance, energy, and exergy analysis of systems that were able to produce power and provide cooling using low-temperature thermal sources.

Zhou et al. (2021) performed the thermodynamic analysis of ORC-VCR systems that assist the air compression system for cryogenic air separation units. The study shows how these systems can be used to improve energy efficiency in low-temperature applications.

Zhar et al. (2021) examined parametric studies and multi-objective optimizations related to Organic Rankine Cycle-Variable Refrigerant Flow systems for improvements in various system parameters and performance measures, focusing on energy inefficiencies and exergy losses reduction strategies. It was noted that improvements of such integrated systems were highlighted by the great improvements made in their energy efficiency and ecological performance.

Zhao et al. (2024) performed a research study for improved solar-driven ORC-VCR-CCHP through a ternary refrigerant selection methodology. Therefore, the research was done to improve the energy and exergy efficiency of the ORC-VCR systems in the applications of solar energies. The authors also used the performance results from different combinations of the refrigerants as one way to conduct an environmental and economic feasibility assessment of the system.

Xia et al. (2024b) investigated systems with two configurations of pure and mixed working fluid ORC-VCR arrangements through multi-objective optimization methods to maximize the performance of such systems. Results showed that mixed fluids were more advantageous in improving the system's efficiency.

Xia et al. (2023b) optimized multi-layer efficiency in the Organic Rankine Cycle-Variable Compression Ratio system. Impacts that identifying the concept may have on overall performances, influenced by operating conditions, working fluids, and heat sources, are investigated. In this regard, the authors were in a position to provide a fairly comprehensive review of several optimization methodologies that have so far been applied for promoting efficiency in energy systems. Accordingly, this paper presents the procedure carried out for the selection of optimal sets of parameters in relation to performance enhancement of the system across a wide operating range. This contribution is relevant when energy conversion and improvement of effectiveness in systems employing ORC-VCR are at stake.

The thermoeconomic analysis by Xia et al. (2023a) for the ORC-VCR systems of varied configurations estimated the optimum variable improvement that can be effected in the performance of the systems through different zeotropic mixtures. It has also been contended that a zeotropic mixture develops thermal efficiency and advances economic benefit privileges.

Tiwari and Soni (2024) performed multi-response optimization of ORC-VCR systems with EDAS method. In this study, optimization of parameters to improve system performance was performed. The study aimed to increase energy efficiency and exergy efficiency by considering various optimization criteria.

The thermodynamic analysis of the ORC-VCR system driven by evacuator and CPC was performed by Tiwari in the year 2024. In the above study, different design and operating parameters have been analyzed for the improvement in the efficiency of such a system. Their results showed that a renewable energy-based ORC-VCR system can run with high efficiency.

Saleh (2018) focused on the analysis of energy and exergy for integrated Organic Rankine Cycle and Vapor Compression Refrigeration systems. The study showed that energy efficiency improvements in such integrated systems can enable heat recovery and cooling applications. Saleh specifically points out that such systems may provide higher overall energy efficiency improvements by more effective use of low-temperature energy sources.

Qureshi et al. (2024) presented a thermal analysis of the integrated solar-driven organic Rankine cycle coupled with a vapor-compression refrigeration system in cascaded manner. The results of this study propose designs that are capable of delivering energy generation and cooling by optimizing the use of solar energy.

Patel et al. (2017) conducted thermoeconomic performance evaluation of a new vapor-compression-absorption system integrated with Organic Rankine Cycle (ORC). The study produced a conceptual analysis on the role played by innovative design systems in achieving energy efficiency and cost-effectiveness.

In the work of Molés et al. (2015), a thermodynamic analysis was carried out on an integrated system of Organic Rankine Cycle and Vapor Compression Refrigeration using low-temperature heat sources and low-GWP fluids. The current paper discusses the results from which fluids give better real performances to the systems while the environmental benefits are outlined with the use of low-GWP fluids. The authors suggest this to be utilized in the creation of energy production and cooling systems that are environmentally acceptable.

The study by Malwe et al. (2022) on dynamic simulation and exergy analyses for Organic Rankine Cycle and Vapor Compression in refrigeration systems showed the integration of both technologies into one to improve energy efficiency through a waste heat source. Therefore, it can be said that the integration of the system enhances very huge gains in terms of efficiency and conservation of energy.

Liang et al. (2021) carried out an experiment to prove refrigeration from thermal sources. He has shown how the ORC can be integrated with the vapor-compression cycles to achieve refrigeration. According to the author, such a feature of the cycles is efficient, especially in heat recovery.

Kim and Perez-Blanco (2015) experimentally found the performance of such integrated energy production and refrigeration systems with the combination of an organic Rankine cycle and vapor-compression cycle. This paper took a look at research pertaining to the effect of low-temperature heat sources on the energy efficiency of the functioning of such systems. The authors agreed with the conclusion that such an all-encompassing approach could conserve energy, as more often than not, it caters to power and cooling needs for a specific application at the same time.

Jiang et al. (2023) did a research to analyze the performance of the ORC-VCR systems utilizing energy obtained from low-grade thermal sources. Indeed, integrated systems adopted in low-temperature heat recovery compression showed higher efficiency than that of the traditional ones. From that, they had established a recommendation that such systems had an enormous potential in industrial heat recovery and energy conservation.

Grauberger et al. (2022) conducted an off-design analysis of an Organic Rankine-Vapor Compression Refrigeration Cycle using R1234ze (E) as the refrigerant. As seen by these researchers, this system performs well for a big span of operational conditions, showing the good influence of low-GWP refrigerants on energy efficiency.

Grauberger, Young, and Bandhauer (2022) experimentally validated an integrated organic Rankine and vapor compression refrigeration system using R1234ze(E) working fluid, which is a low GWP substance. Such a substance can only give positive results if the criteria of energy efficiency and environmental sustainability are taken into consideration.

Bao et al. (2020) conducted a comparative study between single-fluid and dual-fluid systems. In this study, the thermodynamic efficiencies of multiple fluids used in Organic Rankine Cycle - Vapor Compression Refrigeration systems were compared in order to identify the most potential combinations of fluids regarding cooling and energy generation. Their results concluded that, despite the simplicity of single-fluid systems, dual-fluid systems had better thermodynamic advantages.

Asim et al. (2017) reported the organic Rankine cycle-integrated Variable Refrigerant Flow system, developed for waste heat recovery and subjected to complete thermodynamic-thermoeconomic analysis, and further regards economic analysis of energy and cooling produced by the use of waste heat, hence giving recommendations toward cost-effective use of the system.

Alshammari et al. (2023) investigated the performance of integrated Organic Rankine Cycle and Vapor Compression Refrigeration systems using one rotor expander-compressor unit. This paper deals with the capability of such devices in achieving better efficiency from the system point of view. Such technology, according to the authors, has the potential to improve energy conservation for applications with low-temperature differences.

2. Fundamentals of ORC-VCR Systems

The name comes from the so-called Rankine cycle; however, the main distinction is that organic working fluids are employed instead of steam. The traditional Rankine cycle is a high-temperature steam system generally used in major power generation stations. Conversely, Organic Rankine Cycle (ORC) technology facilitates the production of electricity, particularly utilizing low and medium temperature thermal sources such as geothermal energy, biomass, solar energy, and industrial waste heat (Kim & Perez-Blanco, 2015). The organic fluids employed possess lower boiling points in comparison to water, thereby allowing for effective evaporation even under reduced temperature conditions.

ORC consists of an evaporator, turbine (expansion device), condenser and pump as the four major components. The heat source energy is consumed by the evaporator to vaporize the low boiling organic working fluid. Expanded vapour generates energy in the turbine and is routed to the condenser to get back to liquid state. The liquid is returned back to the evaporator by the pump in the process, and the cycle goes on, as shown Figure 1.

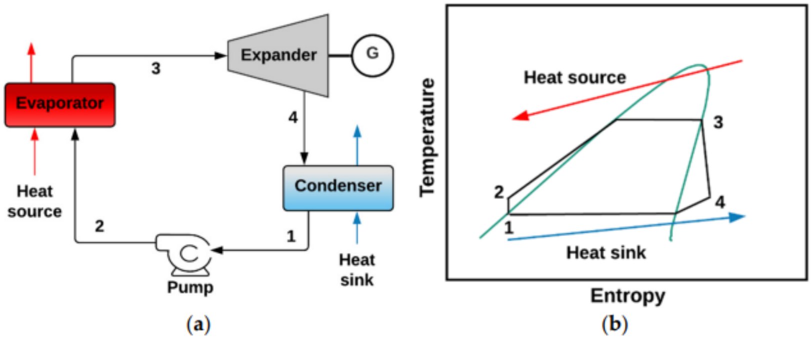

Figure 1. *Basic ORC (a) Schematic diagram (b) T-s diagram (Jiménez-García et al., 2023).*

The VCR represents the most common mechanism in the systems of refrigeration and air conditioning. Such a mechanism allows for the extraction of the thermal energy from the environment that has to be cooled, transformed into vapor at low temperature and pressure by the evaporator, and then compressed by the compressor into a working fluid at higher temperatures and pressures. The high-temperature and pressurized fluid, passing to the condenser, gets condensed there, gives off heat to the atmosphere, and becomes liquid (Molés et al., 2015), as shown Figure 1.

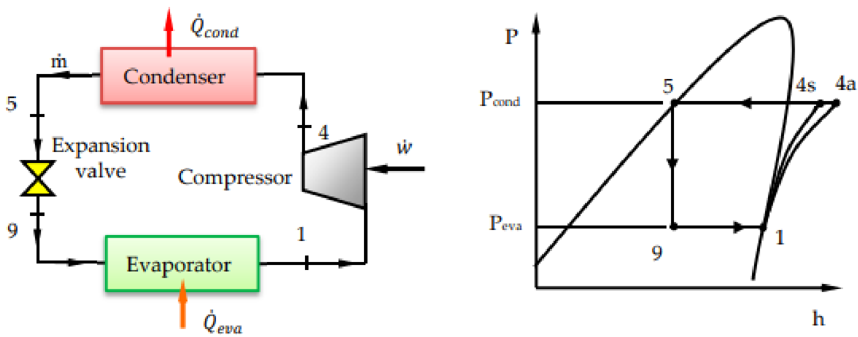

Figure 2. *Basic VCR (a) Schematic diagram (b) P-h diagram (Saleh et al., 2020).*

The main elements that make up the VCR are the evaporator, compressor, condenser, and expansion valve. Its working principle is based on the fact that the compressor compresses the working fluid with mechanical energy. This way, cooling can be achieved in the evaporator and energy conversions can take place between the condenser and expansion valve.

Hybrid ORC-VCR systems, created by combining ORC and VCR systems, offer both energy production and cooling functions simultaneously. In this system, the electrical energy generated by the ORC is used to drive the VCR compressor. Thus, energy recovery is achieved while at the same time cooling is provided at low temperature and low pressure. ORC-VCR systems offer an ideal solution especially for energy saving and environmentally friendly applications (Saleh, 2018), as shown in Figure 3.

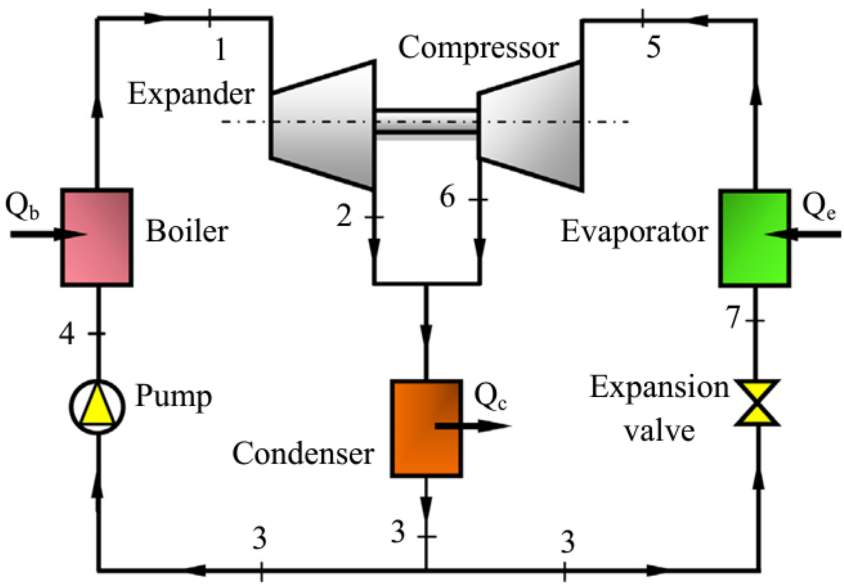

Figure 3. *Basic ORC-VCR (Saleh et al., 2020).*

3. Thermodynamic Analysis and Performance Evaluation

It constitutes a measure of performance of energy conversion in the system, which could also, in general, be expressed by the first law of efficiency. Such an analysis, however, would not account for the quality or usability of energy during conversion; this is where exergy applies as a measure of the potential of energy with respect to work and its recoverability. Exergy analysis of ORC-VCR systems is the essence for loss identification and thermodynamic recoverability optimization (Jiang et al., 2023).

Some performance parameters are exergy efficiency terms in ORC-VCR systems: Coefficient of Performance or COP, electricity generation efficiency, and energy conversion ratios. Exergy efficiency, which quantifies the thermodynamic losses, can stand for the second law efficiency. For example, it was pointed out that “the decreasing exergy efficiency of the system is influenced not only by exergy losses happening at the ORC turbine outlet but also by energy losses occurring at the compressor inlet of the VCR” (Bao et al., 2020).

Various thermodynamic optimization techniques to improve the performance of Organic Rankine Cycle-Variable Compression Ratio systems are targeted toward improving the energy conversion processes while trying to minimize losses. This usually involves optimum sizing of the components of the system, improvement in operational conditions, and use of sophisticated thermodynamic analyses. In this regard, performing a parametric analysis becomes very necessary since, for instance, the optimization of temperature, pressure, and mass flow rates will directly relate to the performance influence of the system as a whole (Zhar et al., 2021).

Actually, the performance of the ORC-VCR system takes into consideration such various parameters as temperature, pressure, and a rate of heat exchanges besides the thermophysical properties of the fluid. Organic fluid critical temperature and pressure used in ORC, for instance, predetermine the value of energy efficiency at outlet of turbine, while in VCR condensation and evaporation temperatures determine the value of COP. According to Liang et al. (2021), a high-temperature and -pressure ratio can further deteriorate the durability of equipment and operating costs while improving the overall performance of the system**.**

4. Working fluids - design of systems

The working fluids of choice strongly dictate the thermodynamic effectiveness and environmental impacts of the ORC-VCR systems. The ideal working fluids selected must have a low Global Warming Potential (GWP) and must also have zero Ozone Depletion Potential (ODP). New generation fluids therefore carry the day in terms of reduced effects on the environment and improved thermodynamic characteristics. R1234ze(E) is one such fluid; it is widely accepted to be used as a refrigerant because of its very low GWP value and high operation efficiency characteristics (Grauberger et al., 2022).

The thermophysical characteristics of working fluids, including density, viscosity, and thermal capacity, are essential for the appropriate sizing of system components and the establishment of operating conditions. Consequently, factors such as exergy efficiency, environmental implications, and safety considerations must be considered when selecting fluids (Saleh, 2016). The properties of the working fluids used in the literature are presented in Table 1 (Xia et al., 2023b)

Table 1. *The properties of the working fluids*

Number	Working Fluid	Molecular mass/ kg·kmol⁻¹	Normal boiling point/K	Critical temperature/K	Critical pressure/ kPa	ODP	GWP	Safety Level
1	R134a	102	247.1	374.2	4059	0	1370	A1
2	R245fa	134	288.3	427.2	3651	0	1030	B1
3	R152a	66	249.1	386.4	4517	0	124	A2
4	R123	153	301	456.8	3662	0	77	B1
5	R236ea	152	279.3	412.4	3502	0	710	B1
6	R245ca	134	298.4	436.2	3502	0	726	B1
7	R290	44	231	369.9	4251	0	3	A3
8	R600a	58	261.4	407.8	3650	0	~20	A3
9	R600	58	272.7	425.1	3796	0	~20	A3
10	R601a	72	301	460.4	3378	0	~20	A3
11	R601	72	309.2	469.7	3370	0	~20	A3
12	R602	86	341.9	507.8	3034	0	~20	A1
13	R1234yf	114	243.7	367.9	3382	0	4	A2L
14	R1234ze	114	254.2	382.5	3640	0	7	A2L
15	R1233zde	131	291.5	438.8	3571	0	7	A1
16	R1336mzzzz	164	306.6	444.5	2903	0	2	A1
17	R1224ydz	148	287.8	428.7	3377	0.88	1	A1
18	R1243zf	96	247.7	376.9	3518	0	1	A2L

ORC-VCR systems can be designed in single-fluid or dual-fluid configurations. Single-fluid systems offer the advantage of simpler design and operation, while dual-fluid systems can increase energy conversion efficiency. In dual-fluid systems, thermodynamic compatibility can be achieved in the ORC and VCR cycles by using two different fluids with different thermophysical properties (Bao et al., 2020).

Much dependence in the design of ORC-VCR systems is based on the available source of heat, energy, cooling requirements, and operating conditions in addition to economic parameters. Thus, proper sizing and integration is required for each module of the system, including evaporator, turbine, compressor, and condenser. The typical configurations include an integrated arrangement of primary heat exchangers, intercoolers, and waste heat recovery devices (Malwe et al. 2022).

5. Optimization and Advanced Design Techniques

Exergy analysis leads to basic tools for conducting optimization studies that would improve the operational efficiency of the ORC-VCR system. Exergy analysis permits the calculation of energy losses and potential recoveries in the different subsystem components. For instance, a reduction in exergy loss at the exit of the turbine, and thus optimal utilization of energy at the entry to the compressor within the framework of the ORC-VCR, will imply great efficiency development for the entire system (Javanshir et al., 2019).

Such kinds of approaches in multi-objective optimization keep a balance between the indication of energy saving and exergoeconomic effectiveness against investments. Commonly used genetic algorithms, multi-criteria decision-making approaches, and artificial intelligence strategies are used in such cases (Zhao et al., 2024).

Advanced data analytics and machine learning methods do find their applications in the performance optimization of ORC-VCR systems. These techniques examine big datasets, make predictions on the performance of such systems, and optimize the processes of energy conversion. Among them, deep learning is important for predicting and optimizing artificial neural network performance in various operating conditions (Xia et al., 2024).

6. Environmental Impact and Sustainability Measures

The ecological impact analysis of the refrigerants used in the ORC-VCR systems is presented, focusing on its GWP and ODP. In this context, the use of natural refrigerants with low GWP together with new synthetic fluids of the latest generation becomes increasingly important (Grauberger et al., 2022).

ORC-VCR system brings out the most viable path to carbon reduction with efficiency improvements in recovering energy. The application of these systems helps to provide a way toward sustainable energy solutions concerning renewable energy sources coupled with industrial waste-heat recovery (Sherwani and Tiwari, 2021).

7. VCR-ORC system exergoeconomic analysis

Exergy-based economic analyses are imperative in designing the most economical ORC-VCR systems. They help to quantify the energy loss and the associated cost through every component of a system (Javanshir et al., 2019).

The optimization strategies developed for the initial investments against operating cost of the ORC-VCR systems are based on thermoeconomic analyses—that means balancing component costs against energy efficiency (Sherwani and Tiwari, 2021).

8. Hybrid Systems: Integration and Energy Storage

Integration of Organic Rankine Cycle-Variable Compression Ratio (ORC-VCR) systems together with storage mechanisms can equalize energy supply and demand. Therefore, integrated configurations can act in synergy with energy storage apparatuses, thereby multiplying the comprehensive energy efficiency and adaptiveness of the system (Malwe et al., 2022).

Combined systems of hybrid ORC-VCR can be linked up with solar power, geothermal power, along with other renewable sources. They might also further enhance the general efficiency of energy by blending merits provided from all the diverse sources of energy (Qureshi et al., 2024).

9. Use of non-conventional sources of energy

Solar energy can also be regarded as another clean and sustainable thermal energy source for ORC-VCR systems. The opportunity for exploring solar-driven ORC-VCR systems integrated with photovoltaic panels and solar collectors could bring an opportunity for the generation of cooling simultaneously with electricity generation. Efficient control strategies with variable solar radiation should be accompanied by the optimum use of high-efficiency heat exchangers in such systems (Zhao et al. 2024; Qureshi et al. 2024).

This means that geothermal power is a renewable heat resource with, at the least, an ORC-VCR temperature. One of the numerous variant types of renewable resources proposed to enhance efficiency in energy use and decrease carbon emissions includes organic geothermal power, done through use with Organic Rankine Cycle and vapor-compression cycle by utilizing heat taken out from low-temperature wells (Sabbaghi et al. 2024).

10. Dual Purpose Energy Systems- ORC-VCR Integration

ORC-VCR systems are ideally very well suited for cogeneration applications—by this, it is meant the simultaneous production of combined heat and power—also for trigeneration, during which the generation of heat, power, and cooling goes on simultaneously. It can be electric power and refrigeration produced simultaneously from one heat source in these novel-generation systems. This approach makes energy use in industrial and commercial buildings very efficient and saves on resources (Patel et al., 2017).

The use of ORC-VCR systems for recovering waste heat can also efficiently be produced through various industrial processes or energy production units. The recent ones are designed specially in such a manner that they may reduce energy consumption to its minimum with proper reduction in operational cost as this specific cycle allows recovery and thereafter reutilization of the produced waste heat (Asim et al., 2021).

11. Application in Regional and Small-Scale Energy Systems

Applying micro-cogeneration results in relatively high amounts of electric and thermal energies when the basis of application is small-scale. Besides other major contributions, innovation and construction related to micro-cogeneration ORC-VCR systems are highly essential in finding and utilizing the resources of energy efficiently. As a matter of fact, this is one of the most sustainable ways through which energy demand can best be met across any specific environment, such as urban and rural places alike (Tashtoush et al., 2020).

12. Energy Polies and ORC-VCR Systems

Policies and regulations that are aimed at promoting energy efficiency should be carefully designed for this kind of activity to make sure that the proliferation of Organic Rankine Cycle - Vapor Compression Refrigeration (ORC-VCR) systems is effectively supported and encouraged. In this regard, energy-related policies have a tremendous potential to direct such integrated energy systems' development and implementation in endorsing and promoting the use of a portable renewable source of energy. In so doing, taxes reduction and other forms of incentives presented by the government can be strong instruments for speeding the process of acceptance and practical application of the system, resulting in a more sustainable approach to energy use (Tiwari, 2024).

13. Future Directions and Implementation

ORC-VCR systems have achieved high utilization throughout most industries in critical waste heat recovery while capturing geothermal energy, solar energy, and many other kinds of renewable energy. This innovative system finds diversified applications, including the enhancement of energy efficiency and effective reduction of carbon emission in various cement, steel, chemical, and petrochemical industries, among others.

Future investigations will be focused on finding new working fluids that may bring efficiency improvements with respect to different working fluids and developing new system configurations to ensure overall performance is improved. There also could be developed advanced control strategies that will allow the optimization of these systems towards better performances and there is a huge scope for the ORC-VCR system to find its place in sustainable energy solutions. Moreover, low carbon footprint technologies in this area of research are going to pay much more attention to further development and advancement in this very field alone.

14. Conclusion

ORC-VCR systems combine into their construction both Organic Rankine Cycle and Vapor Compression Cycle principles. They demonstrate very high potentials for energy recovery and efficiency. It is really special, taking into account that they are able to provide energy and cooling output from hot sources at low and middle temperatures, which is usually the temperature at which heat is lost. By using low heat temperatures, the ORC-VCR systems contribute state-of-the-art solutions not only to boosting general efficiency related to energy production but also to alleviating environmental impacts from energy production as well as from applications for cooling. These systems help in sustainable energy management due to the benefits of integration with renewable energy sources, recovery of waste heat, and use of low-GWP fluids. Further improvement of performance in ORC-VCR systems is also contributed to by the adoption and application of advanced materials and technologies, intelligent control strategies, and energy policy-compliant design. Due to their small-scale energetic solutions and regional applications, their applicability and effectiveness have increased under a wide range of scenarios. This is mainly attributed to the fact that the application area and different technological innovations that have been brought into the ORC-VCR system combine to give a good approach toward energy efficiency maximization, economic cost, and environmental sustainability.

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BÖLÜM 2

TABAKALI NANOKOMPOZİTLERİN GENEL DEĞİŞKEN ŞARTLARDAKİ YORULMA DAVRANIŞLARI

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Not: Doktora tezinden üretilmiştir.

Elyaf takviyeli kompozitlerde nanopartikül katkısının yorulma, burkulma ve darbe davranışına etkisinin deneysel olarak

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Danışman: PROF. DR. NUMAN BEHLÜL BEKTAŞ

Tez No: 538616

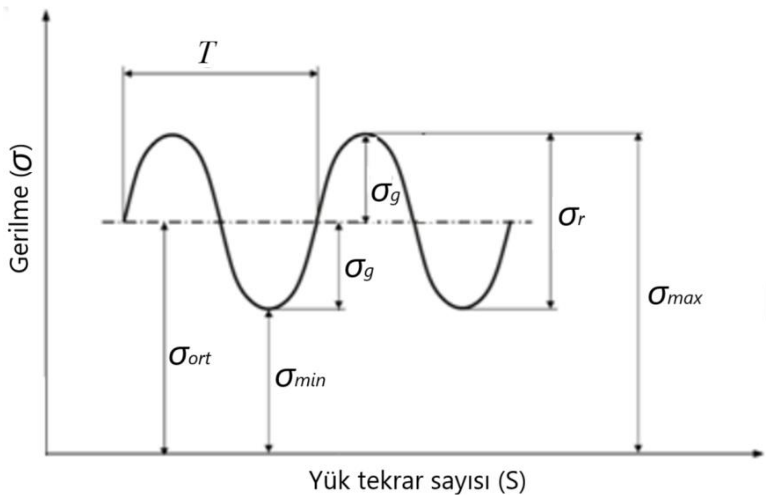
1. Giriş

Son yıllarda havacılık, otomotiv ve denizcilik endüstrilerinde elyaf takviyeli kompozitlere olan artan talep, bu malzemelerin özelliklerini daha iyi anlamak ve daha iyi mühendislik ürünleri elde etme için bu malzemelerde artan bir araştırma ihtiyacına neden olmuştur (Peng ve ark. 2007, Khashaba ve ark. 2017, Biercuk ve ark. 2002, Dindar B., Bektaş, N.B., 2018). Literatürde nanokompozitler ile ilgili çalışmalar sınırıdır bunlardan bazıları; Karbon/epoksi kompozitlerde yorulma dayanımının deleminasyon üzerindeki etkisi incelenerek, deleminasyonun yorulma testi sırasında çekme oranın arttırılmasıyla da etkili bir şekilde arttığını ifade etmişlerdir (Khan ve ark., 2010). İki tür cam elyaf/epoksi kompozitin, tek yönlü ve rastgele elyaf astarlı, bükülme altıdaki yorulma davranışları karşılaştırmışlar ve cam elyaf takviyeli kompozitin çatlak yayılma direncinin rastgele kompozisyondan iyi olduğunu ifade etmişlerdir (Selmy ve ark. 2013). Kemik kırıklarının tedavisi için karbon/keten/epoksiden oluşan yeni bir kompozite yorulma analizi yapmışlardır. Analizde numuneler çekme dayanımlarının % 50'si ile yüklemişler ve araştırmanın sonunda 2 x 10^6 yük tekrar sayısında kompozitin yalnızca % 0.48'i kadar bir çatlak oluşumu gözlemişlerdir. Sonuçlardan bu malzemenin kemik kırığı tedavilerinde kullanılmak üzere yeterli yorulma dayanımına sahip olduğu düşüncesi oluşmuştur (Bagheri ve ark 2014). Karbon/epoksi kompozitlerin farklı yönlendirme açılarındaki yorulma davranışlarını incelemişler ve eksenel yönlnedirmenin 45° açılı yönlendirmeden daha iyi sonuçlar verdiğini ifade etmişlerdir (Weiss ve ark 2010).

Bu çalışmada kompozitler tek eksenli kumaşlardan üretilmiş [(0,+45,-45, 0,+45,- 45,-45,+45,0,-45,+45,-0)] oryantasyonda ve aynı oryantasyonda üç eksenli kumaşlardan üretilmiş olan kompozitler [(0,+45,-45)(0,+45,-45)(- 45,+45,0)(-45,+45,-0)] olmak üzere ve bunların karbon nanotüp (KNT) katkılı ve katkısız haldeki numunelerinin çekme dayanımları belirlenerek devamında yorulma dayanımları belirlenmiştir. Çalışmada kompozit numuneler el yatırması metodu kullanılarak üretilmiştir. KNT partikülleri ise reçineye sonikatör kullanılarak homojen bir şekilde dağıtılmıştır. KNT'ler reçineye ağırlıkça %0,5 oranında katılmıştır. Literatür taraması sonucunda bu oranın en iyi faydayı sağladığı sonucuna varılmıştır ve bu yüzden bu oran seçilmiştir. Bunun nedeni KNT'ler bu orana kadar dayanımı arttırmakta ve sonrasında topaklanmalar başlayarak kompozit malzemede gerilme yığılmalarına sebep olarak kompozit malzemenin dayanımını azaltmaktadır. Bu çalışmanın literatürden farkı elyaf dizilimleri ve KNT modifiyesidir (Dindar 2019).

1.1 Yorulma Yükleme Durumları

Yorulma, malzemelerin çekme dayanımlarının altındaki dayanabildikleri yük tekrar sayısı olarak tanımlanabilir. Yorulma yükleri grafikle gösterildiğinde yük değişimleri genellikle sinüzoidal olmaktadır. Tekrarlı yüklemeler; genel değişken şartlarda (R=0.1), dalgalı değişken şartlarda (R=0) ve tam değişken şartlarda (R=1) yüklemeler olarak sınıflandırılabilir. Bu çalışmada yorulma deneyleri Şekil 1'deki gibi genel değişken şartlarda yapılmıştır.



Şekil 1: Genel değişken yükleme durumu

Burada gerilmeler σ_{max}. maksimum üst gerilme ve σ_{min}. minimum alt gerilme arasındadır. Ortalama gerilme ise σ_{ort} maks. ve min. gerilmelerin ortalaması alınarak bulunmaktadır. Ortalama gerilme Denklem 1 kullanılarak hesaplanmaktadır.

$$\sigma_{ort} = \frac{\sigma_{max} + \sigma_{min}}{2} \quad (1)$$

Gerilme aralığı σr; Denklem 2' deki gösterildiği gibi maksimum ve minimum gerilme arasındaki farktan hesaplanmaktadır.

$$\sigma_r = \sigma_{max} - \sigma_{min} \tag{2}$$

Gerilme genliği σg; gerilme aralığının yarısıdır. Denklem 3'deki gibi hesaplanmaktadır.

$$\sigma_g = \frac{\sigma_r}{2} = \frac{\sigma_{max} - \sigma_{min}}{2} \tag{3}$$

Gerilme oranı (R) ve genlik oranı (A) olarak iki tür tekrarlı yorulma yapılmaktadır ve Denklem 4'deki gibi hesaplanmaktadır.

$$Gerilme\ oranı; R = \frac{\sigma_{min}}{\sigma_{max}}, genlik\ oranı\ ; A = \frac{\sigma_g}{\sigma_{ort}} \quad (4)$$

Ek olarak, Yük frekansı= f=$\frac{1}{T}$ (*Hz*), Yük tekrar sayısı=N, Periyot süresi=T (s) şeklinde ifade edilmektedir.

1.2 S-N Eğrileri

S-N eğrisi, malzemede yorulma hasarının meydana geldiği yük tekrar sayısına karşılık gelen gerilmeyi ifade etmektedir. S-N eğrileri elde edilirken gerilme ve yük tekrar sayıları logaritmik olarak hesaplanır. S-N eğrileri deneysel yada numerik olarak oluşturulabilmektedir. Genellikle deney cihazı metodu tercih edilmektedir. Bu metod ile yorulma numunesi deney cihazına bağlanır ve numunede çatlak yada hasar oluşana kadar tekrarlı bir şekilde yük uygulanmaktadır S-N eğrileri genellikle grafiğin sol üst köşesinden başlayarak yükün azalması ile birlikte sağ alt tarafa doğru eğimli bir şekilde ilerlemektedir. Bu, yüksek gerilme uygulanan yüklemelerde, düşük gerilme uygulanan yüklemelere nazaran yorulma hasarının daha az çevrimde oluştuğunu göstermektedir. Bu tip bir yorulma deneyinde, yük tekrar sayılarının frekansı, hasar oluşumunu meydana getiren yük tekrar sayısını değiştirmez. Bir S-N eğrisinin oluşturulmasında yorulma numunelerinin farklı gerilme yüklerinde test edilmesi ve sonuçların logaritmik olarak grafiğinin oluşturulması gerekmektedir (serdarkarakurt.com, 2019). Bazı metaller, sonsuz yorulma ömrüne sahip olabilmektedir. Uygulanan gerilmeler bu malzemeleri hasara uğratmak için belirli bir seviyenin altında kalırsa, hasar oluşumu meydana gelmeden sonsuz sayıda çevrime dayanabilmektedirler. Kompozit malzemelerde ise yük tekrar sayısı 10^6'dan fazla ise sonsuz ömür kabul edilmektedir (serdarkarakurt.com, 2019).

2. MALZEME ve YÖNTEM

Bu bölüm, kompozit numunelerin üretimini, çekme ve yorulma deneylerini ve bu çalışmalardan elde edilen sonuçları içermektedir. Bu çalışmada kompozitler tek eksenli kumaşlardan üretilmiş [(0,+45,-45, 0,+45,- 45,-45,+45,0,-45,+45,-0)] ve üç eksenli kumaşlardan üretilmiş kompozitler [(0,+45,-45)(0,+45,-45)(-45,+45,0)(-45,+45,-0)] olmak üzere ve bunların KNT (karbon nanotüp) katkılı ve katkısız haldeki numunelerin çekme dayanımları belirlenerek devamında yorulma dayanımları belirlenmiştir. Çalışmada kompozit numuneler el yatırması metodu kullanılarak üretilmiştir. KNT partikülleri ise reçineye sonikatör kullanılarak homojen bir şekilde dağıtılmıştır. KNT'ler reçineye ağırlıkça %0.5 oranında katılmıştır. Literatür taraması sonucunda bu oranın en iyi faydayı sağladığı sonucuna varılmıştır ve bu yüzden bu oran seçilmiştir. Bunun nedeni KNT'ler bu orana kadar dayanımı arttırmakta ve sonrasında topaklanmalar başlayarak kompozit malzemede gerilme yığılmalarına sebep olarak kompozit malzemenin dayanımını azaltmaktadır. Bu çalışmanın literatürden farkı elyaf dizilimleri ve KNT modifiyesidir.

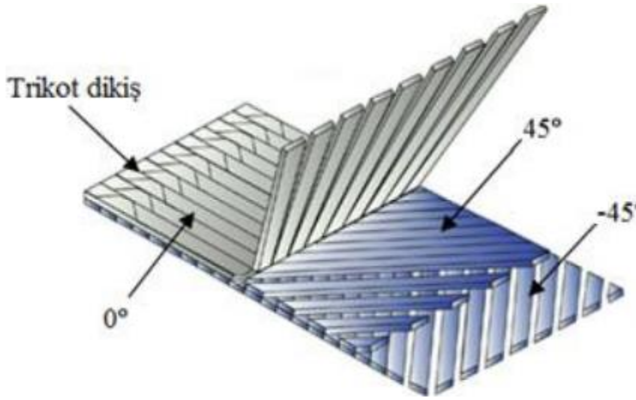
2.1. Malzeme

Kompozit numuneler takviye kumaşları, reçine ve nanopartiküller olmak üzere üç kısımdan meydana gelmektedir. Bu kısımlarda kullanılan malzemelerin genel bilgileri Tablo 1'de verilmiştir.

Tablo 1: Kompozit üretiminde kullanılan malzemelerin genel özellikleri.

Epoksi Reçine	Kürleştirici	Takviye Elemanı	Nanopartikül	Kumaşların Elyaf Oryantasyonları
Araldite LY-1564	Aradur-3487	E-Cam Karbon	Karbon nanotüp	Üç eksenli (0,+45,-45) ve Tek eksenli (eksenel)

Çok eksenli takviye kumaşların uygulamaları son zamanlarda hızla yaygınlaşmaktadır. Şekil 2'de üç eksenli takviye kumaşının görüntüsü yer almaktadır.



Şekil 2: Üç eksenli dikişli, kıvrımsız kumaş yapısı (Ağır, 2012).

E-cam ve karbon kumaşlar üç eksenli (0,+45,-45) ve tek eksenli olmak üzere iki farklı tipte temin edilmiştir. Bu kumaşların özellikleri Şekil 3'de verilmiştir.

Üç Eksenli E-Cam Kumaş			
	Tabaka	Fiber Türü	Alan Ağırlığı
1	0°	900+1200 Tex	413 gr / m2
2	+45°	300 Tex	200 gr / m2
3	90°	200 Tex	12 gr / m2
4	-45°	300 Tex	200 gr / m2
5	Dikiş	76 Dtex	10 gr / m2

Tek Eksenli E-Cam Kumaş			
	Tabaka	Fiber Türü	Alan Ağırlığı
1	0°	1200 Tex	283 gr / m2
2	90°	68 Tex	37 gr / m2
3	Dikiş	76 Dtex	10 gr / m2

Üç Eksenli Karbon Kumaş			
	Tabaka	Fiber Türü	Alan Ağırlığı
1	0°	1600 Tex - 24K Carbon	300 gr / m2
2	45°	800 Tex - 12K Carbon	300 gr / m2
3	45°	800 Tex - 12K Carbon	300 gr / m2
4	Dikiş	76 DTex	5 gr / m2

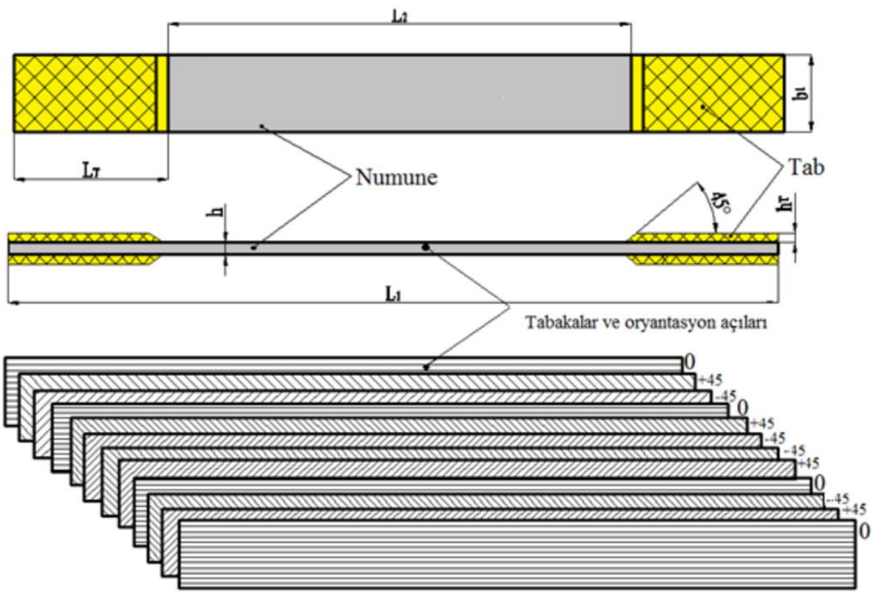
Tek Eksenli Karbon Kumaş			
	Tabaka	Fiber Türü	Alan Ağırlığı
1	0°	12K Carbon	317 gr / m2
2	Dikiş	1100 DTex	17 gr / m2

Şekil 3: Takviye kumaşlarının yapıları.

2.2. Numunelerin Üretilmesi

Numuneleri tamamı el yatırması metodu ve sıcak presleme ile üretilmiştir. Nanokompozitlerin dayanımını etkileyen faktörlerin başında, partiküllerin matris içinde homojen dağılması ve nanopartiküllerin matris ile elyaf arasında ara yüzey bağı oluşturması gelmektedir (Eskizeybek 2012). Bu çalışmada kullanılan -OH fonksiyonelli çoğul duvarlı karbon nanotüp (ÇDKNT) partikülleri Ege Nanotek şirketinden tedarik edilmiştir. Bu partiküller ultrasonikasyon metodu ile reçineye uygulanmıştır. Dağıtım (homojenizasyon) Hielscher UP 400 S sonikatör ile 400 watt çıkış gücünde, %70 genlik ile 0,6 frekans'ta 35 dk. ile karışımın sıcaklığı kontrol edilerek yapılmıştır. Reçine 4/1 sertleştirici oranında ve ağırlıkça %0.5 KNT ilaveli olarak hazırlanmıştır. Üretimi yapılan kompozitlerin kumaşları ilgili elyaf rulolarından uygun ölçülerde kesilerek düzgün bir masa üzerine yerleştirilmiş ve hazırlanan reçine, nanopartikül karışımı kumaşlara emdirilmiştir. Epoksi reçine emdirilmiş bu kumaşlar mikro hava baloncuklarının uzaklaşarak epoksi reçinenin kumaşlara daha iyi emilmesi sebebiyle on gün beklemeye alınmıştır. Elde edilen reçine emdirilmiş kumaşlar mumlu kuşe kağıt ile sarılarak kürlenmesi için sıcak presleme yöntemi ile preslenerek 6 bar basınçta, 120 °C sıcaklık ile iki saat kürlenmeye tabi tutulmuştur.

Daha sonra Tablo 2'deki geometrik ölçülerde olacak şekilde kompozit levhalardan su jeti ile kesim yapılmıştır. Su jeti ile kesim metodu kompozit numunelerde oluşabilecek kesim hatalarını ve kesim esnasında oluşabilecek ısınmayı önleyerek kaliteli bir kesim sağlamıştır. Çekme ve yorulma deneyleri için oluşturulan numunelerin yapısı Şekil 4'de verilmiştir (Dindar 2019).



Şekil 4: Deney numunesi şematik gösterimi (Dindar 2019).

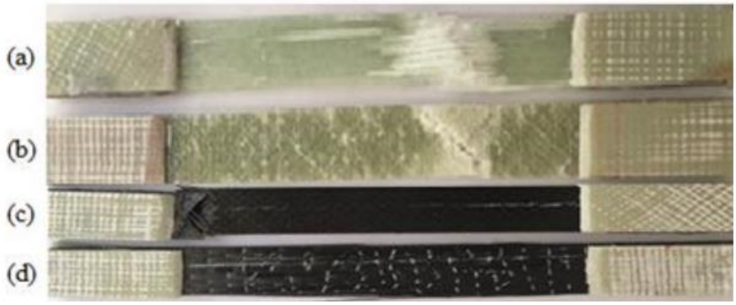
Tablo 2'de şematik gösterimi verilen numunenin ebatları yer almaktadır. Burada karbon elyaf takviyeli kompozitler ile E-cam takviyeli numunelerin ebatları farklıdır. Bunun sebebi karbon elyaf takviyeli numuneler yüksek çekme dayanımlarına sahip olmaları sebebi ile test cihazının yükleme kapasitesinin yetersiz kalmasındandır (Dindar 2019).

Tablo 2: Karbon/epoksi ve E-cam/epoksi numunelerin boyutları (Dindar 2019).

Sembol	Karbon/epoksi (mm)	E-cam/Epoksi (mm)
L_1	250	250
L_2	150	150
L_T	50	50
b_1	15	25
h	4	3
h_T	3	3

3. BULGULAR

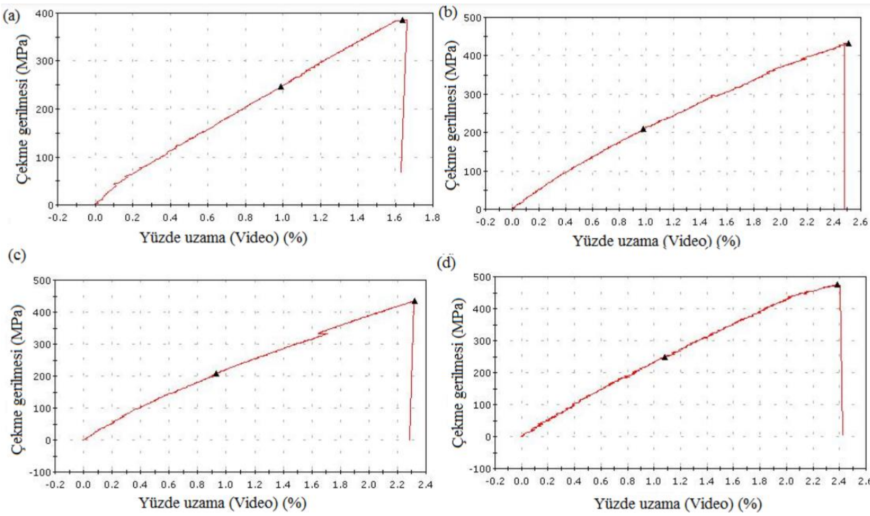
Kompozit numunelerin çekme deneyleri oda şartlarında ASTM 3039 D kompozit çekme standardına referans alınarak 0.5 mm/dakika hızında deplasman kontrollü gerçekleştirilmiştir. Şekil 5'de deneyler sonrası numunelerde oluşan hasarlar görülmektedir.



Şekil 5: Hasarlı deney numuneleri, (a) Tek yönlü kumaşlı E–cam/Epoksi, (b) Üç eksen kumaşlı E-cam/Epoksi, (c) Tek yönlü kumaşlı Karbon/Epoksi, (d) Üç eksen kumaşlı Karbon/Epoksi. (Dindar, 2019)

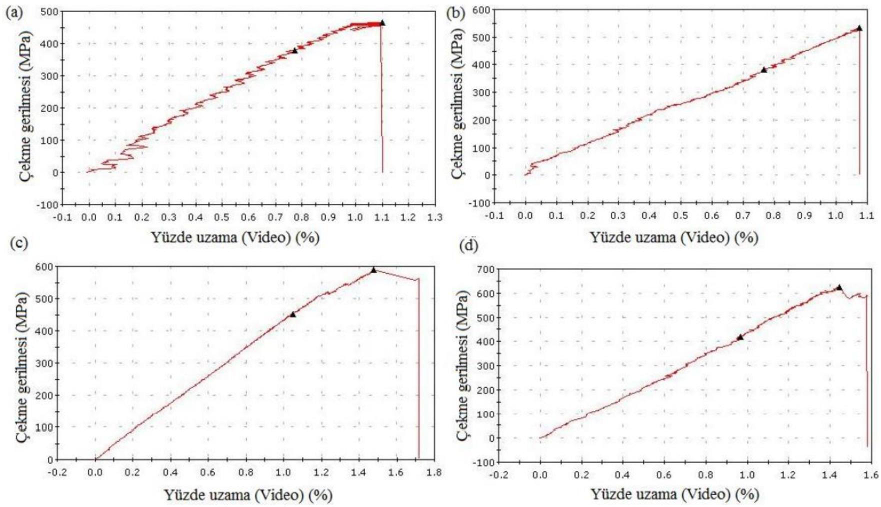
3.1 Çekme Deneyleri

Şekil 6'da E-cam takviyeli katkılı ve katkısız kompozitlerden elde edilen çekme grafikleri verilmiştir. (Şekil 6 (a))'da üç eksenli kumaşlardan oluşturulmuş E-cam/Epoksi'ye ait çekme diyagramı, (Şekil 6 (b))'de üç eksenli kumaşlar ile oluşturulmuş olan E-cam/Epoksi/KNT katkılı numuneye ait diyagram, (Şekil 6 (c))'de tek yönlü kumaşlar ile oluşturulmuş olan E-cam/Epoksi'nin diyagramı ve son olarak (6 (d))'de tek yönlü kumaşlardan oluşturulmuş olan E-cam/Epoksi/KNT katkılı kompozitlere ait diyagram yer almaktadır (Dindar 2019).



Şekil 6: E-Cam ile takviye edilmiş kompozitlerin çekme diyagramları: Üç eksenli E-Cam/Epoksi (a), Üç eksenli E-Cam/Epoksi/KNT (b), Tek eksenli E-Cam/Epoksi (c), Tek eksenli E-Cam/Epoksi/KNT (d) (Dindar 2019).

Şekil 7'de Katkılı ve katkısız olarak deneyleri yapılmış olan karbon elyaf takviyeli kompozitlerin çekme deney grafikleri verilmiştir. (Şekil 7(a))'da Üç eksenli kumaşlardan üretilmiş olan katkısız Karbon/Epoksi'nin çekme diyagramı, (Şekil 7(b))'de üç eksenli kumaştan elde edilen Karbon/Epoksi/KNT katkılı numunenin diyagramı, (7(c))'de tek eksenli kumaştan elde edilen Karbon/Epoksi katkısız numune ve (Şekil 7(d))'de yine tek yönlü kumaş ile takviyelendirilmiş olan Karbon/Epoksi/KNT kompozite ait çekme diyagramı görülmektedir (Dindar 2019).

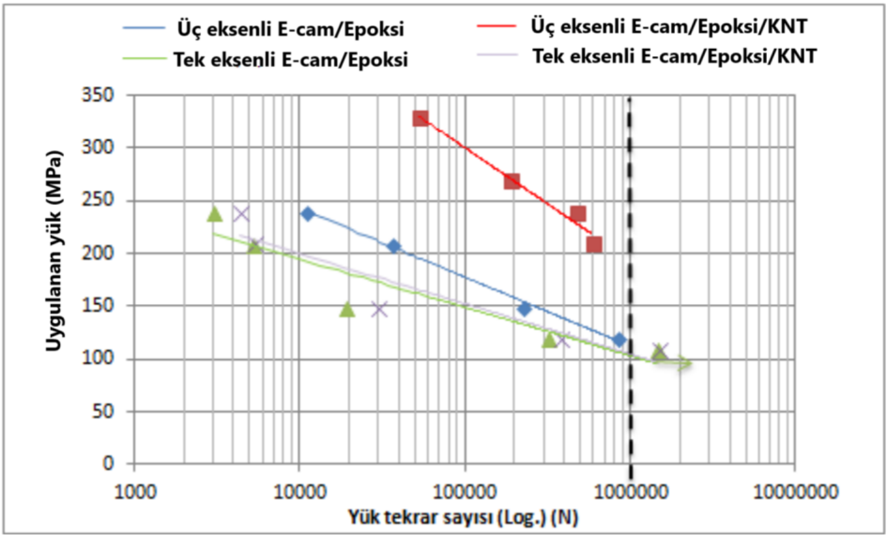


Şekil 7: Karbon ile takviye edilmiş kompozitlerin çekme diyagramları: Üç eksenli Karbon/Epoksi (a), Üç eksenli Karbon/Epoksi/KNT, Tek eksenli Karbon/Epoksi (c), Tek eksenli Karbon/Epoksi/KNT (d) (Dindar 2019).

3.2 Yorulma Deneyleri

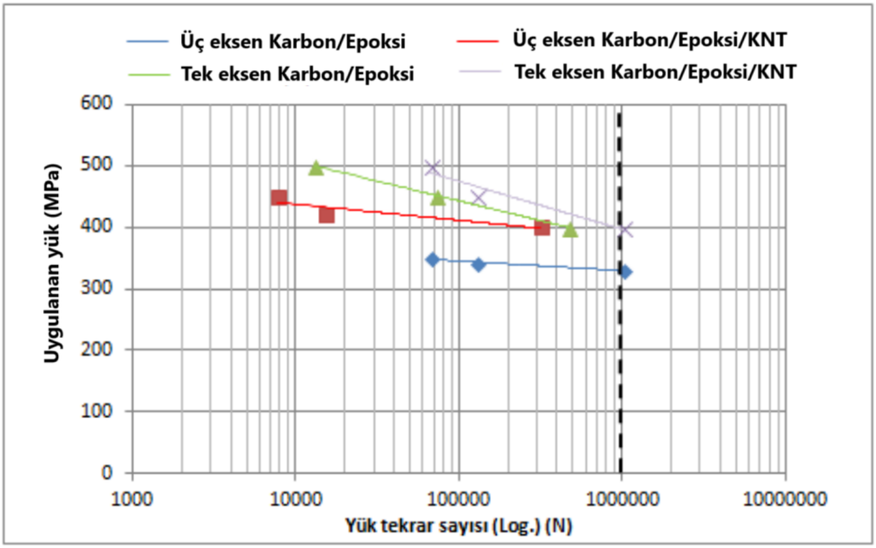
Yorulma deneyleri genel değişken şartlarda, çeki-çeki yükü altında R=0.1 ile yapılmıştır. Karbon takviyeli kompozitler 3 Hz frekans ile E-cam takviyeli kumaşlar ise 10 Hz frekansta Instron 8801test cihazında yapılmıştır. Karbon elyaf takviyeli kompozitlerin frekansının düşük tercih edilmesinin nedeni bu kompozitlerin yüksek yorulma mukavemetine sahip olmaları ve bundan dolayı yüksek yorulma yükleri uygulanmasıdır. Test cihazı 3 Hz'in üzerindeki frekanslarda bu yükleri karbon takviyeli numunelere tam anlamı ile uygulayamamaktadır. Yapılan testler sonucunda katkılı ve katkısız kompozit plakaların S-N (Wöhler) eğrileri oluşturulmuştur. Testler yüksek gerilme genliklerinde üçer defa tekrar edilirken zaman gereksiniminden dolayı sonsuz yorulma ömrüne giden numunelerin deneyleri birer kez yapılmıştır.

Üç eksenli ve tek eksenli E-Cam takviyeli kompozitlerin (S-N) diyagramları Şekil 8'de verilmiştir. Üç eksenli kumaş takviyeli katkılı E-cam/Epoksi/KNT numuneler en iyi yorulma performansını göstermiş ve yorulma dayanımları azalan sıra ile üç eksenli kumaş takviyeli E-cam/Epoksi, tek yönlü kumaş takviyeli katlkılı E-cam/Epoksi/KNT ve tek yönlü kumaş takviyeli E-cam/Epoksi kompozitler şeklindedir. KNT modifiyesinin kompozit plakanın yorulma dayanımını arttırdığı gözlemlenmiştir. Burada sonuçların üç eksenli kumaş takviyelilerde, tek eksenli kumaş takviyelerine kıyasla yüksek çıkmasının sebebi kumaş yapısıdır. Kumaş özelliklerine bakıldığında üç eksenli E-Cam kumaşlar (0° yönü 413 g/m^2, 2100 TEX, 45° yönlü elyaflar, 200 g/m^2, 300 TEX), tek eksenli E-cam kumaşlar ise 300 g/m^2 ağırlığındadır. Kompozitlerin belirli bir yöndeki dayanımını belirleyen kriterlerin başında o yöndeki elyafların miktarı önemli rol oynar. Üç eksenli kumaşların yapısı gereği 0° yönünde 413 g/m^2 ağırlığında elyaf bulunurken tek eksenli kumaşla takviyelendirilmiş kompozitlerde 0° 300 g/m^2 ağırlığında elyaf bulunmaktadır. Kumaşların bu yapılarından dolayı üç eksenli kumaşlardan imal edilen kompozitlerin yorulma değerleri çekme değerlerine benzer olarak yüksek çıktığı görülmüştür (Dindar 2019).



Şekil 8: E-Cam ile takviye edilmiş kompozitlerin S-N (Wöhler) eğrileri (Dindar 2019).

Şekil 9'da dikişli üç eksenli kumaş ile takviyeli kompozitler ve tek eksenli karbon kumaşlarla takviyelendirilmiş katkılı ve katkısız kompozitlerin yorulma Wöhler (S-N) grafikleri verilmiştir. Burada yorulma dayanımları azalan sıra ile tek yön katkılı, tek yön katkısız, üç eksenli katkılı, üç eksenli katkısız olarak sıralanmıştır. Çekme deneylerindeki gibi yorulma deneylerinde de karbon kumaşlar çekme performanslarına benzer davranmışlardır. Yorulma testleri yüksek tekrarlı çekme testleri olarak düşünüldüğünde çekme ve yorulma testlerinin uyumlu olması gayet doğaldır. Yorulma dayanımlarının tek yönlü kumaş ile takviyelendirilmiş kompozitlerde yüksek çıkmasının sebebi reçinenin tek yönlü kumaşlarda yüzeylere iyi bir şekilde uygulanması olarak düşünülmektedir. Burada karbon nanotüp modifiyesi her iki kumaş tipinde de dayanımda artış sağlamıştır (Dindar 2019).



Şekil 9: Karbon ile takviye edilmiş kompozitlerin S-N (Wöhler) eğrileri (Dindar 2019).

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BÖLÜM 3

DIGITAL MOCK-UP MANAGEMENT IN AEROSPACE INDUSTRY

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1. Introduction

Throughout the course of human history, the processes of product development and design have undergone significant evolutionary changes, particularly within the aviation sector over the past century. The transformation of business practices and their resultant impacts, coupled with the remarkable innovations of this era, have brought the concept of complexity to the forefront of academic inquiry. This complexity is characterized by the often-unpredictable behaviors and outcomes associated with dynamically evolving systems. Despite initial efforts to establish a sound framework and architecture, the development process has faced substantial challenges due to both internal and external influences, as well as the scale of the projects involved.

Subsequent technical advancements and development processes, which include the identification of customer needs and requirements, have been able to gain traction through the foundational drawing data that underpins design efforts. In particular, 2D technical drawings play a crucial role during the early phases of design. These drawings, produced by engineers, are essential for conveying ideas in the later stages of the design process and serve as the groundwork for production. To ensure that these drawings communicate effectively with a broader technical audience, establishing standardized drawing conventions is vital. Consequently, a deeper understanding of drawing quality in the initial design stages enhances effectiveness, as the transition from abstract concepts to concrete forms during the design maturation and development phases necessitates a three-dimensional representation and a visual experience as defined at Sibois et.al., (2013).

The development of three-dimensional physical models has become a crucial necessity for comprehending the visual aspects of design, the interrelationship of components, their arrangement, and their functional behavior, irrespective of one's awareness of the associated challenges. However, the complexities involved in physical production, material sourcing, interdisciplinary collaboration, and change management have rendered physical prototype studies increasingly intricate. This situation has highlighted the need for a more comprehensive preliminary design phase. It has become essential to transform numerous two-dimensional technical drawings into a coherent three-dimensional structure that can be interpreted across various disciplines. At this juncture, Computer-Aided Design (CAD) technologies have been adopted, leading to the emergence of "Virtual Product Development," which represents a more advanced iteration of the traditional two-dimensional approach. This advancement allows for the digital simulation of physical prototyping, facilitating the resolution of numerous issues more efficiently, with enhanced quality and reduced costs during the stages of product development and innovation. Consequently, the establishment of a Digital Mock-Up and the foundational elements of the Digital Mock-Up process within Product Data Management (PDM) and Product Lifecycle Management (PLM) have arisen from this necessity as mentioned in Dai et.al., (2020).

This discipline has been established to enhance the efficiency of Design Model Utilization (DMU) processes within industrial contexts and has nearly become a benchmark in advanced manufacturing sectors. Over the past three to four decades, DMU has served as a foundational element in the design processes of the aviation industry. It is essential to convey information, processes, and methodologies that have not been adequately documented in scientific literature but have evolved within organizations into practical applications for future use. The primary aim of this research is to refine the DMU design processes within the sector and analogous industrial environments, to manage intricate systems more proficiently, to boost operational efficiency, and to sustain activities in a controlled and agile manner. Furthermore, it seeks to promote development through collaborative interactions, thereby fostering the dissemination of this discipline and culture.

1.1. What is DMU

Numerous definitions of Digital Mock-Up (DMU) exist within the academic literature. Garbade & Dolezal (2007) characterize a DMU as a digital three-dimensional representation of a product, inclusive of its structures and attributes. This digital model is enhanced by various activities that contribute to the comprehensive description of the product. The DMU facilitates engineers in the design and configuration of intricate products, enabling them to validate their designs without the necessity of constructing a physical prototype. In a different approach, Döllner et.al., (2000) define DMU as a computer-based representation of a tangible product, comprising documents, attributes, and structures. A DMU encapsulates a well-defined dataset within the product model, while the term “product model” encompasses all information accumulated throughout the product development lifecycle. Gausemeier et.al., (2000) do not distinguish between Digital Mock-Up and Virtual Prototype, asserting that the fundamental concept is to develop computer models that address all pertinent aspects of the product under development, thereby minimizing the time and costs associated with creating physical prototypes. Berchtold, (2000) situates the DMU within its developmental context, describing it as a comprehensive virtual working environment that supports the entire process chain of three-dimensional development and management of complex products, incorporating effectiveness and variant control.

Digital Mock-Up (DMU) refers to an extensive product depiction, generally presented as a three-dimensional model in an engineering framework. Within the realm of complex development processes, DMU is of great importance, as it ensures accurate visualization, encourages collaborative efforts, and allows for extensive analysis, which significantly minimizes both costs and the time needed for development with innovative approach.

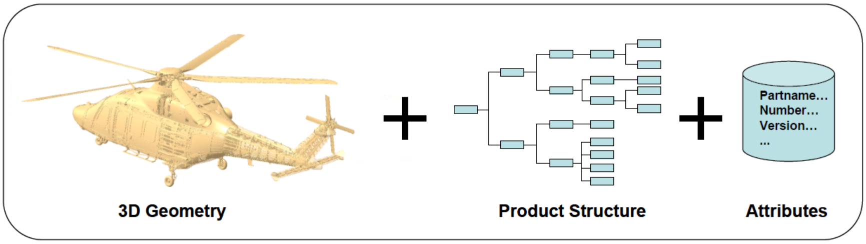


Figure 1 DMU of Gokbey helicopter

The application of various techniques and technologies supports the use of lightweight 3D models that offer multiple levels of detail. By leveraging efficient data structures such as JT (NX data format) and CGR (Catia data format), engineers are able to visualize, analyze, and interact with large quantities of product data in real-time on standard desktop computers. This framework establishes a direct interface between Digital Mock-Ups and Product Data Management (PDM) systems. Moreover, Active Digital Mock-Up technology combines the visualization of assembly mock-ups with the capabilities to measure, analyze, simulate, design, and redesign. The DMU department is responsible for coordinating all aspects of 3D data, including the management of clashes, clearances, and the verification of 3D data requirements across all relevant departments.

1.2. Why DMU is needed?

In recent years, the requirements for Sundays have evolved in response to intensifying competition, necessitating innovation and variability. This variability is influenced by various factors, including quality, innovation, cost efficiency, and configuration. However, as noted by McLay, (2014), such variability introduces complexity and challenges in management.

To address these issues, it has become essential to streamline design processes, making them more agile and manageable in light of ongoing changes. This approach aims to reduce product costs and production timelines while enhancing quality and efficiency. Consequently, investments in CAD and digital technologies have been prioritized to meet the evolving demands for quality and innovation. During the development phase, companies strive to sustain their knowledge by virtualizing different stages of the product lifecycle, thereby increasing adaptability and establishing a comprehensive data archive. Strategies that integrate various departments and stakeholders around a shared knowledge base enhance the efficiency of engineering processes.

Mengoni & Germani, (2006) assert that the economic benefits of creating and utilizing a Digital Mock-Up (DMU) and its associated processes can be quantified and are evident in areas such as conceptual layout, communication, decision-making, prototyping, installation, maintenance, and certification. Therefore, a robust engineering and manufacturing DMU infrastructure is essential for effective collaboration with units and suppliers, facilitating data exchange through a common language, methodology, and processes that accommodate both internal and external influences.

1.3. DMU for Systems Engineering

Systems engineering functions as an efficient management paradigm according to Vosgien, (2015) with a multidisciplinary orientation. The DMU engages in a multitude of tasks relevant to the platform across different phases, intricately linked with systems engineering. It particularly collaborates with various disciplines in accordance with the V-chart depicted in Figure 2.

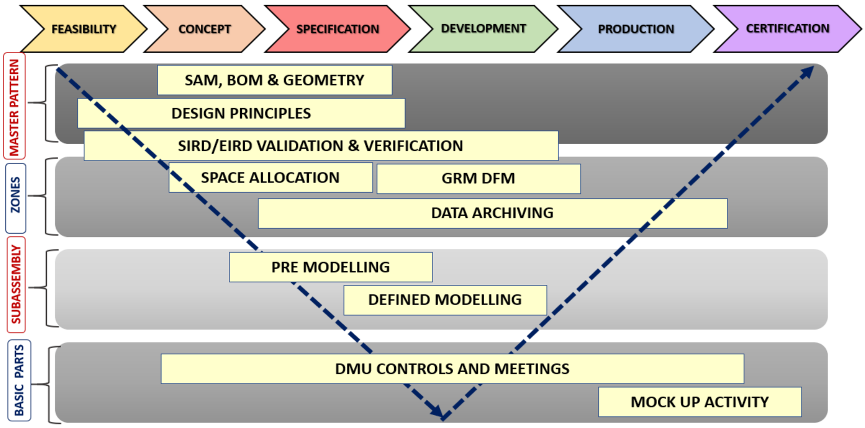


Figure 2 DMU V charted process in system engineering Life-cycle phases

The DMU produces diverse outputs that illuminate systems engineering activities on the platform, especially concerning the arrangement and spatial relationships of equipment, systems, and elements. It adopts varying roles across different regions and phases. A key output is the DMU review report, which serves as a documentary record addressing various Proof of Concept (PoC) issues as mentioned at Siboiset et.al., (2013). Furthermore, the System Installation Requirement Document (SIRD) is responsible for ensuring that the model is developed in alignment with the specified requirements.

1.4. DMU elements & processes

A DMU product structure is composed of both geometric data and associated metadata. This data is systematically recorded within the product life cycle management system, which features an engineering and productivity-oriented hierarchical assembly framework, collectively referred to as the product structure. Each component of the product is represented through CAD modeling, where each model serves as an individual element. These elements are organized according to a specific hierarchical arrangement—such as assembly order, system-based, or regional-based—culminating in the formation of a product tree. The models are created in CAD software in a one-to-one representation, capturing their geometric characteristics and potentially indicating their spatial relationship to the primary region within the design environment or on the platform. When models are intended for holistic display, they are often simplified, which may result in the loss of certain original data attributes, including features, design history, and color. Although this simplification reduces the disk space required, it enhances the efficiency of automation processes due to the ease of control. Geometric detail information is integrated within these models, and a significant portion of their metadata is retained in the PLM system as Figure 3. The management of these processes is illustrated in Figure 3, with design units evolving from low to high maturity levels. At the initial stages, design teams oversee individual designs, while the DMU team is tasked with the overarching assembly, which includes the integration of the DMU model and ensuring the quality of the components as mentioned in Riascos et.al., (2015).

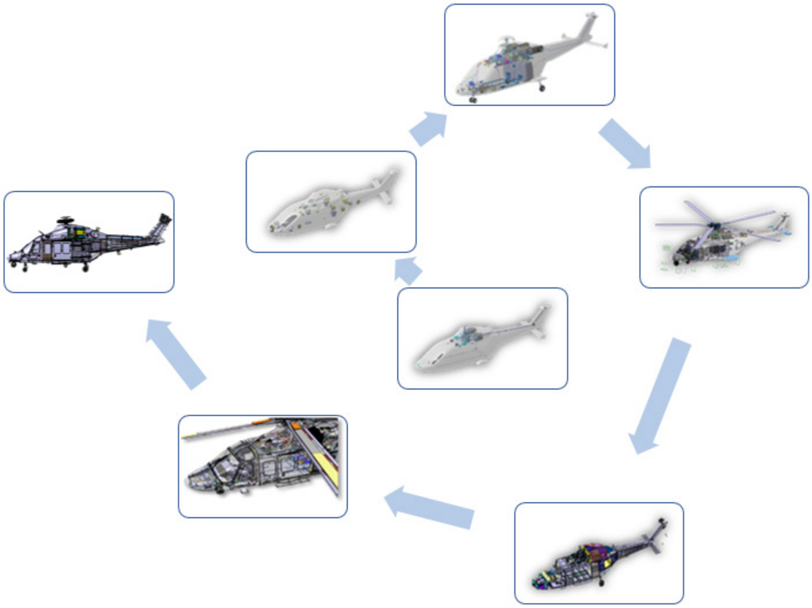


Figure 3 Evolution of Gokbey helicopter DMU CAD Model

1.5. PLM and DMU relationship

DMU serves as an essential element in product lifecycle management (PLM). It functions as a critical component that captures a comprehensive overview of the product lifecycle throughout all phases of development, adopting a holistic perspective on PLM management from inception. Within the framework of DMU, the maturity of the product is meticulously monitored throughout the entire lifecycle, facilitating analyses related to clashes and clearances, maintenance considerations, holistic assembly principles, production phases, and assembly scenarios, thereby enabling comprehensive product oversight and design execution. Furthermore, DMU plays a pivotal role in the archiving of various data within product data management, encompassing data archiving, trade-off management, change management, and revision tracking. All information pertinent to PLM, including reporting, issue management, and resolution, is securely maintained within the DMU. This data is also managed interactively on a process-oriented basis within the PLM framework. DMU acts as both a management and integration tool within PLM. By establishing an integrated structure with CAD on the PLM platform, DMU facilitates a transparent view of the development project's progress, effectively supporting the interdisciplinary engineering process through the workflows designed in various product structure techniques and tools. A PLM life cycle process and DMU models are shared at Figure 4.

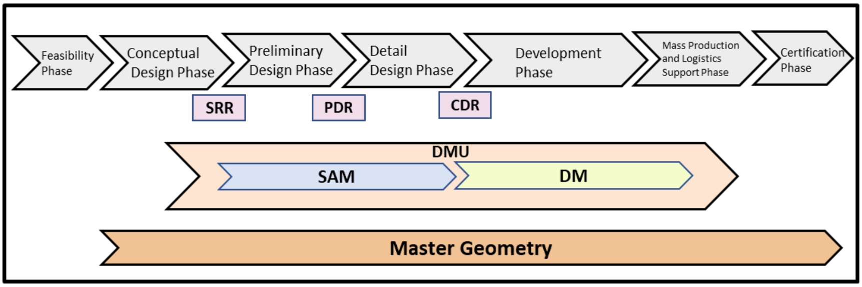


Figure 4 DMU studies at PLM phases.

2. Methodology

The field of Digital Mock-Up (DMU) includes various methodologies that correspond to its goals and roles within a system. The core components of this subject are well-defined. Unlike theoretical literature, this discussion focuses on a practical, experience-based perspective. DMU application fields and tools.

2.1. DMU collaborative working mentality

One of the primary goals of DMU is to enhance collaboration among multidisciplinary teams. By providing a shared digital environment, DMU enables engineers, designers, and project managers to work together more efficiently, identifying potential issues early in the design process. This collaborative approach not only streamlines communication but also fosters innovation, as team members can explore various design alternatives and assess their feasibility in real-time.

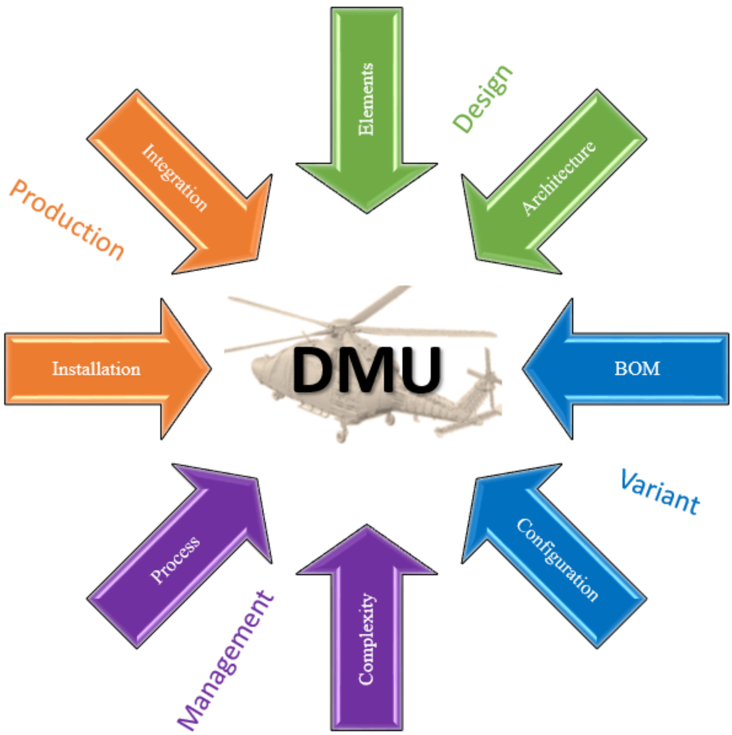


Figure 5 Perspectives of DMU roles with different discipline

As illustrated in Figure 5, the Digital Mock-Up (DMU) engages with various disciplines for distinct objectives and assumes multiple roles. It is involved in the management of processes and complexity from an administrative perspective. Within this framework, DMU conducts research focused on the design of lean processes, the effective multidisciplinary execution of these processes, and the sustainable management of data in technical contexts, all while adhering to established rules aimed at minimizing complexity. Regarding variant management, DMU adopts a comprehensive approach to the development of product structures and product trees, coordinating configuration management with Product Lifecycle Management (PLM) to ensure team alignment. It oversees processes to ensure that all requirements are addressed efficiently and collaborates with the systems engineering discipline to lay the technical groundwork and establish the design infrastructure from the outset. In this regard, DMU is tasked with ensuring that all models generated in Computer-Aided Design (CAD) are accurately designed and positioned according to established guidelines, conforming to the systematic nature of interdisciplinary collaboration while facilitating the identification and resolution of inter-system issues. In environments where the "As Designed as Built" principle is implemented, it is the responsibility of DMU to guarantee that both assembly and production processes are executed as specified, and that all data generated throughout the process is systematically archived. In terms of interdisciplinary collaboration, DMU actively promotes the adoption of this mindset across all involved disciplines.

2.2. SAM process

Space allocation models (SAM) are developed following the decomposition of initial requirements and the establishment of master geometry (March & Cangelir, 2013). These models provide fundamental geometric references and define the product architecture within CAD, delineating essential systemic and regional boundaries. The boundaries are established by identifying the region, which is a three-dimensional volumetric area, utilizing the "on-site design" methodology. This approach underpins the three-dimensional CAD design process. An example of a SAM showed at Figure 6.

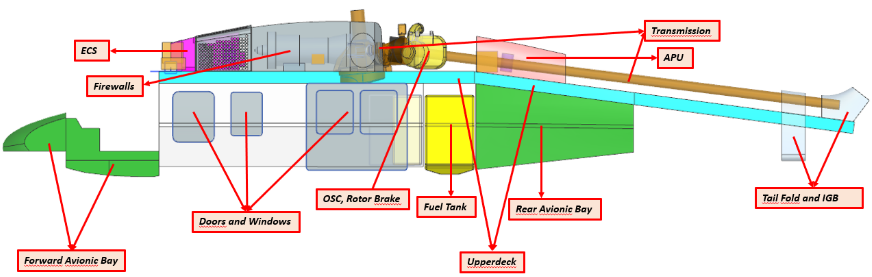


Figure 6 SAM preparation of a helicopter

Based on these references, the respective design teams recognize their interactions with other teams within the Digital Mock-Up (DMU) model hierarchy, allowing them to refine their design processes in alignment with the defined volumetric limits and data references. The DMU model also encompasses three-dimensional data related to kinematic mechanisms, sweeping volumes, and dynamic equipment across various phases. Furthermore, all models incorporate openings to facilitate the passage of transmission equipment, such as harnesses and pipes, associated with the systems. Symmetrical components are parametrically modeled in relation to one another as required, for instance, in the case of left and right wings. SAMs are capable of identifying conflicts, as they are not yet fully developed models; the primary objective is to validate system integration at the earliest possible stage.

2.3. BOM process

The responsibility for developing the top-level Bill of Materials (BOM) tree lies with the Design Management Unit (DMU). This critical task involves creating a comprehensive and organized representation of all components, subassemblies, and materials required for the product. The BOM serves as a foundational document that guides the entire product development process, ensuring that all necessary elements are accounted for and properly categorized.

Once the foundational product tree is established, designers proceed to integrate their models into this structure as Figure 7. This integration process involves aligning individual design components with the overarching BOM framework, ensuring that each part is accurately represented and linked to its corresponding assembly. Designers must collaborate closely to ensure that their contributions fit seamlessly into the established hierarchy, maintaining consistency and clarity throughout the product development lifecycle.

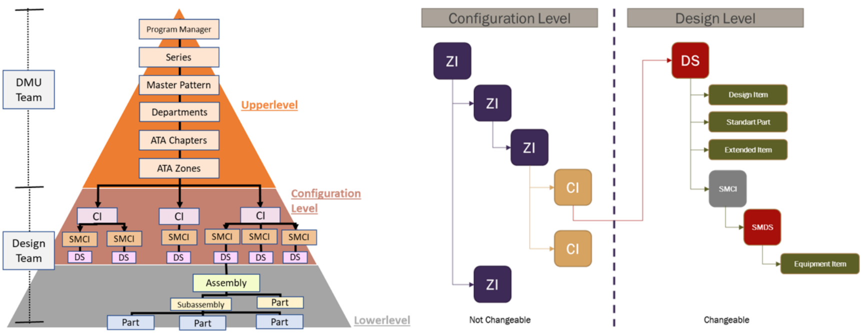


Figure 7 BOM structure of platform

Oversight and administration of the Product Breakdown Structure (PBS) are managed by both the DMU and Configuration teams. The PBS is a critical tool that provides a visual representation of the product's components and their relationships, facilitating better understanding and communication among team members. The DMU plays a key role in ensuring that the PBS aligns with the overall design objectives and requirements, while the Configuration teams focus on maintaining the integrity of the product structure throughout its development. Together, these teams work to ensure that any changes or updates to the BOM and PBS are accurately reflected and communicated, thereby supporting effective project management and product delivery. This collaborative approach helps to mitigate risks, streamline processes, and enhance the overall quality of the final product.

2.4. DM (Definite Model) process

Following the establishment of the SAM (System Architecture Model) and the BOM (Bill of Material) or PBS (Product Breakdown Structure) frameworks within the DMU (Digital Mock-Up) context, designers embark on a comprehensive journey to enhance the sophistication and functionality of the model. This phase is critical as it lays the groundwork for the subsequent stages of product development. To begin with, designers meticulously integrate detailed design elements into the DMU model. This includes the application of GD&T (Geometric Dimensioning and Tolerancing), which provides a clear and precise method for defining the allowable variations in the geometry of the components. By employing GD&T, designers ensure that each part meets the necessary specifications for fit, form, and function, thereby reducing the risk of errors during manufacturing and assembly. In addition to GD&T, material specifications are carefully selected and documented. This involves choosing the appropriate materials that not only meet the performance requirements of the product but also align with cost, sustainability, and manufacturability considerations. The inclusion of material specifications in the DMU model allows for a more accurate representation of the product's physical properties and performance characteristics. Furthermore, assembly techniques are incorporated into the DMU model, detailing how various components will be assembled into the final product. This includes considerations for tooling, fastening methods, and assembly sequences, which are crucial for ensuring efficient production processes and minimizing assembly errors.

As these detailed design elements are integrated, they are organized into geometric reference sets and annotation notes within the PMI (Product Manufacturing Information) data. This structured approach not only enhances the clarity of the design but also facilitates communication among team members and stakeholders, ensuring that everyone has access to the same information. The culmination of this intricate process is the creation of the Definite Model (DM). This model represents a comprehensive and finalized version of the product design, incorporating all the necessary details and specifications. Once the DM is completed, it is published on relevant platforms, making it accessible to all stakeholders involved in the product development process as seen at Figure 8.

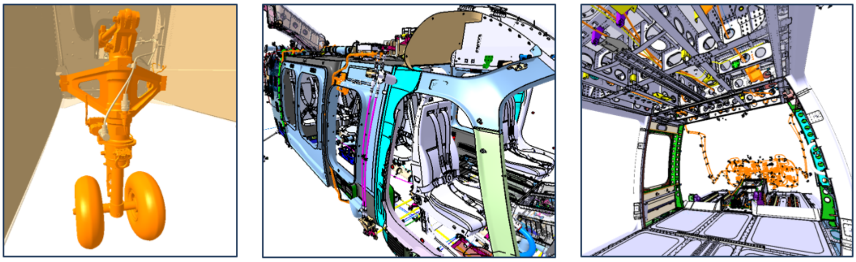


Figure 8 DM model of Helicopter

Additionally, the DM is documented in the PLM (Product Lifecycle Management) system. This documentation is vital for maintaining a centralized repository of information that can be easily accessed and referenced by engineers, designers, project managers, and other stakeholders throughout the product lifecycle. By ensuring that the DM is integrated into the PLM system, organizations can enhance collaboration, streamline workflows, and improve overall project efficiency. In summary, the transition from the initial SAM and BOM/PBS frameworks to the creation of the Definite Model involves a detailed and systematic approach to design enhancement.

2.5. Clash/clearance & other analyses

Clash and clearance analyses are conducted utilizing the DM model alongside CAD software programs, including NX and Catia. This methodology involves performing analyses at various levels, specifically the helicopter level, subsystem level, and regional level of the helicopter, as illustrated in Figure 9.

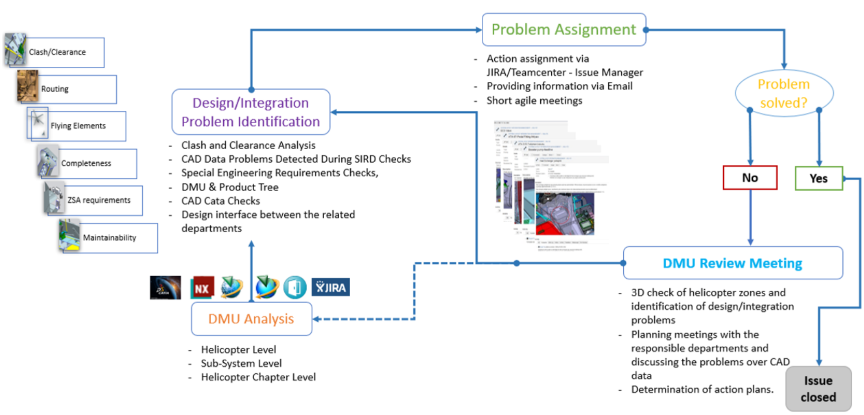
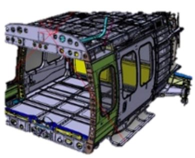


Figure 9 DMU problem detecting and solving methodology

In addition to analyzing clash clearance, various issues that CAD programs are unable to identify are also examined. These include CAD data inconsistencies, unique engineering challenges, maintenance and accessibility concerns, as well as Bill of Materials (BOM) discrepancies. Such issues are documented and communicated to the appropriate designers via Product Lifecycle Management (PLM) systems like JIRA or Teamcenter. Beyond clash and clearance issues, the analysis also encompasses routing difficulties, unassigned element issues, completeness concerns, Zonal Safety Analysis challenges, and maintenance-related problems. For the detection of additional issues, a review of the Digital Mock-Up (DMU) CAD model is conducted from an engineering standpoint. While clash analyses are carried out on a regional basis, regional guide matrices, as illustrated in Figure 10, are established to minimize workload and avoid redundant examinations of the same areas. This approach has been previously showed as the matrix of the aircraft section level MICM in the literature by Jian et.al., (2021).



	Center Fuselage Structural Assembly	Doors and Fairings	Windshield and Windows	Center Avioncs	Equipment and Furnishings	Harness (Center+Fuel)	Fuselage Systems
Center Fuselage Structural Assembly	X	X					
Doors and Fairings		X		X		X	X
Windshield and Windows	X	X					
Center Avioncs	X			X		X	X
Equipment and Furnishings	X			X	X	X	
Harness (Center+Fuel)	X					X	X
Fuselage Systems	X	X			X		X

Figure 10 DMU clash & clearance analyze check matrix

After identifying the problem, it is reported to the appropriate design unit as part of the process management implementation on the selected platform. If deemed necessary, meetings are organized among the design units to facilitate discussion. If the issue persists, a DMU Review Meeting is scheduled, involving all designers to present the problem and notify other units about the situation. The action items are then addressed based on the decisions made during the meeting. Once the problem is resolved, it is documented and archived.

2.6. Integrating design teams

Monitoring the Digital Mock-Up (DMU) is an essential practice that serves as a valuable metric for the coordination of multidisciplinary frameworks within project management. The DMU acts as a comprehensive representation of a product or system, integrating various elements such as design, engineering, and manufacturing data. By closely monitoring the DMU, organizations can assess critical factors such as quality, Computer-Aided Design (CAD) data accuracy, maturity levels of the design, and the achievement of DMU milestones. These factors collectively inform both internal and external strategies, ensuring that all relevant stakeholders are aligned and informed throughout the project lifecycle.

For example, when a significant number of DMU-related issues arise—such as conflicts between design elements or a lack of completeness in the deliverables from a specific design team—these issues can serve as indicators of underlying problems. Such problems may stem from a deficiency in the team's experience, which can hinder their ability to navigate complex design challenges effectively. Additionally, ineffective communication with other stakeholders can exacerbate these issues, leading to misunderstandings and misalignments in project goals. An underestimation of design complexity can also contribute to these challenges, as teams may not allocate sufficient resources or time to address intricate design requirements. Furthermore, inadequate staffing levels can strain the team's capacity to meet project demands, resulting in delays and increased costs. The implications of these DMU-related issues are significant, as they can ultimately lead to project delays and budget overruns. Therefore, it is crucial for project managers and team leaders to proactively identify and address these challenges to maintain project momentum and ensure successful outcomes. Moreover, the DMU provides management stakeholders with a unique opportunity to engage in clear and effective communication with clients.

By utilizing the DMU as a visual and interactive tool, stakeholders can facilitate the acquisition of direct and precise feedback from clients regarding their expectations and requirements. This feedback can then be relayed to other stakeholders who may need to act, ensuring that everyone involved is on the same page and working towards common objectives. This process greatly enhances the transparency of project advancement, allowing for real-time updates and insights into the project's status. As noted by Riascos et.al., (2015), early identification of potential issues is critical for mitigating risks and ensuring that projects remain on track. By leveraging the DMU as a central communication hub, organizations can foster collaboration, streamline decision-making, and ultimately drive project success. In summary, effective monitoring of the DMU not only serves as a metric for assessing project health but also as a catalyst for improved communication and coordination among all stakeholders involved.

3. Results and Discussions

3.1. Clash & Clearance report

Clash & Clearance analysis identifies allocation errors in the Digital Mock-Up (DMU) before assembly, often using brute force methods. It is highly automatable, with most vendors offering collision detection modules. This process involves analyzing the intersection of two planes within triangles that represent the parts being examined, falling under computational geometry. The analysis starts with loading the DMU and calculating geometric intersections dynamically, considering various constraints during part movement. Results are logged, detailing the colliding parts, collision specifics, and intersection data. Experts review these findings to assess their significance and decide on necessary redesigns, though not all collisions require scrutiny. Certain collisions, such as those involving screw threads, flexible components, or tightly fitting parts, can often be disregarded or anticipated as Figure 11.

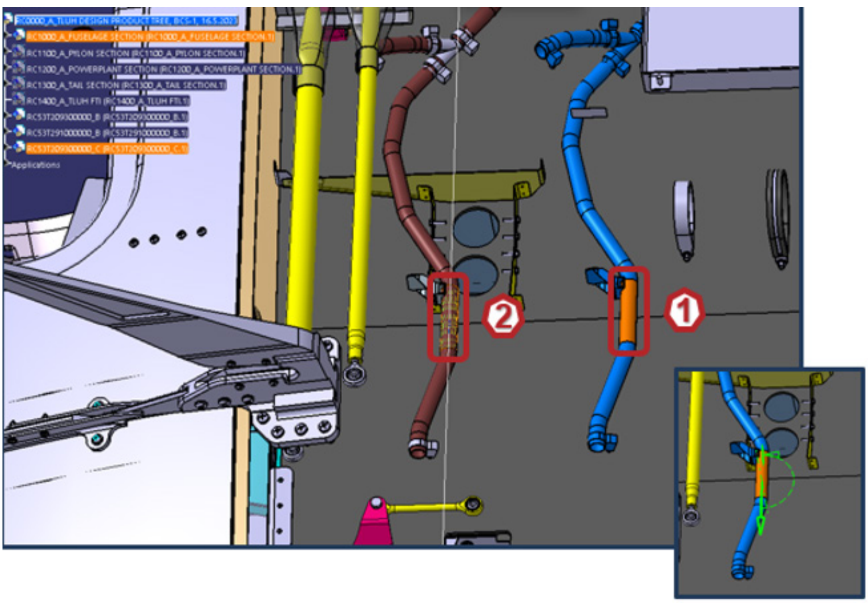


Figure 11 Clash samples of CAD data

After conducting a comprehensive analysis of clash & clearance, detailed reports are generated and distributed to the design team. These reports serve as a critical resource for the designers, who are tasked with developing effective solutions to any identified issues. The clash analysis component of this process is specifically aimed at identifying and preventing overlaps between various elements within the design. This is crucial, as overlaps can lead to significant functional and structural problems in the final product.

In addition to clash analysis, the clearance analysis plays a vital role in ensuring that all components within the Computer-Aided Design (CAD) data are positioned according to the specified spacing requirements outlined in the layout guidelines. This aspect of the analysis is essential for maintaining the integrity of the design, as it ensures that there is adequate space between components to allow for proper operation, maintenance, and safety.

The reports generated from these analyses provide a clear overview of any potential conflicts or spacing issues, allowing designers to prioritize their efforts effectively. By addressing these concerns proactively, the design team can implement necessary adjustments and modifications to the CAD models, thereby enhancing the overall quality and functionality of the final product. This iterative process of analysis and solution development is fundamental to achieving a successful design outcome, ultimately leading to a more efficient and reliable product that meets all specified requirements.

3.2. Managing problems

There are several widely recognized methodologies employed for effectively managing problems across various fields and industries. One such methodology, as depicted in Figure 12, is specifically crafted to streamline the complexities associated with these issues. By simplifying the problem-solving process, this approach not only makes it easier to identify and address challenges but also enhances the overall implementation of necessary actions. The primary focus of this methodology is on the Decision-Making Unit (DMU) problems, which are critical to ensuring that these issues are managed appropriately. By concentrating on the intricacies of DMU-related challenges, the methodology aims to facilitate a structured approach to problem resolution. This structured approach is essential for achieving effective outcomes, as it allows for a more organized and systematic way of tackling issues that may arise during the design and development phases.

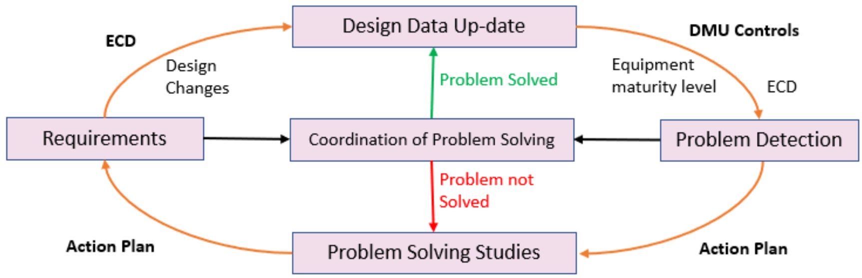


Figure 12 Problem management strategy of DMU

Moreover, this methodology promotes collaboration among design teams, enabling them to work together in a coordinated manner. By fostering an environment of teamwork and communication, the methodology ensures that all team members are aligned in their objectives and strategies. This collaborative effort not only enhances the quality of the solutions developed but also accelerates the decision-making process, leading to timely and effective resolutions. The methodology illustrated in Figure 12 serves as a valuable tool for managing DMU problems. Its emphasis on simplification, structured management, and collaborative teamwork ultimately contributes to more successful outcomes in problem-solving endeavors. By adopting this approach, organizations can enhance their ability to navigate challenges and drive innovation within their design teams.

3.3. Integration management

A Concurrent Engineering (CE) strategy is vital for enabling the simultaneous collaboration of multiple designers from diverse disciplines on the same product within shared spatial environments. This approach requires a Digital Mock-Up (DMU) to serve as the central hub for information exchange. The DMU should be supported by primary Product Data Management (PDM) systems that handle complementary geometric information. It is essential to maintain continuous information sharing throughout the development stages of the DMU, from the initial design phase to production, as this enhances coordination and improves team integration. In this framework, the DMU integrator plays a crucial role in unifying the teams involved in the product's development and implementation across various phases as mentioned at Herlem et.al., 2013. An example shared at Figure 13 for integration management design to implementation.

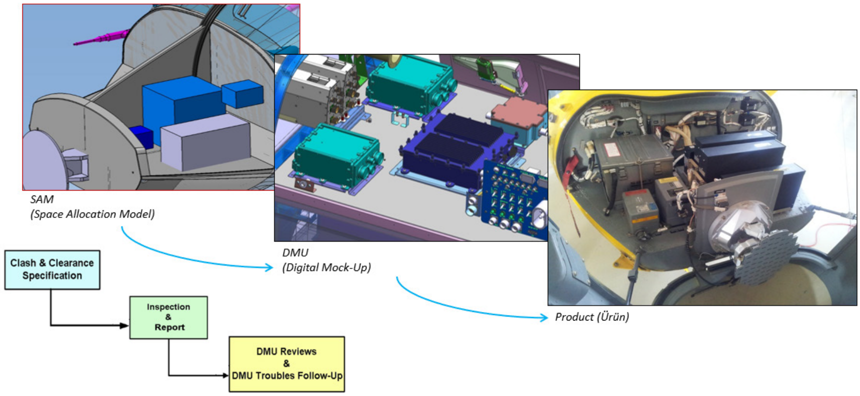


Figure 13 Integration Management of DMU

3.4. Solving problems

The responsibility of addressing problems within an organization is not solely the duty of the Designated Management Unit (DMU). While the DMU plays a crucial role in problem-solving, it is important to recognize that effective resolution of issues often requires collaboration and input from various stakeholders across different departments. To enhance its effectiveness, the DMU employs a proactive and productive strategy that involves organizing regular team meetings. These meetings serve as a platform for open communication, allowing team members to share their insights, experiences, and expertise. By fostering an environment of collaboration, the DMU encourages diverse perspectives, which can lead to more innovative and comprehensive solutions.

In addition to facilitating discussions, the DMU also leverages advanced tools such as Computer-Aided Design (CAD) data. This technology enables the team to visualize complex problems and explore potential solutions in a more interactive and detailed manner. The use of CAD data not only aids in the identification of issues but also assists in the development of practical solutions that can be implemented effectively. This approach is particularly beneficial when the DMU collaborates with multidisciplinary teams. By bringing together individuals with varied backgrounds and areas of expertise, the DMU can tackle intricate challenges that may be beyond the scope of any single discipline. The combination of diverse skill sets and knowledge allows for a more holistic understanding of the problems at hand, leading to more robust and sustainable solutions. While the DMU has a significant role in addressing problems, it recognizes the importance of collaboration and the value of utilizing advanced tools like CAD data.

By organizing team meetings and working alongside multidisciplinary teams, the DMU enhances its ability to navigate complex challenges and drive effective problem-solving initiatives within the organization. As shown at Figure 14, a basic problem collecting and defining template had created by DMU team.

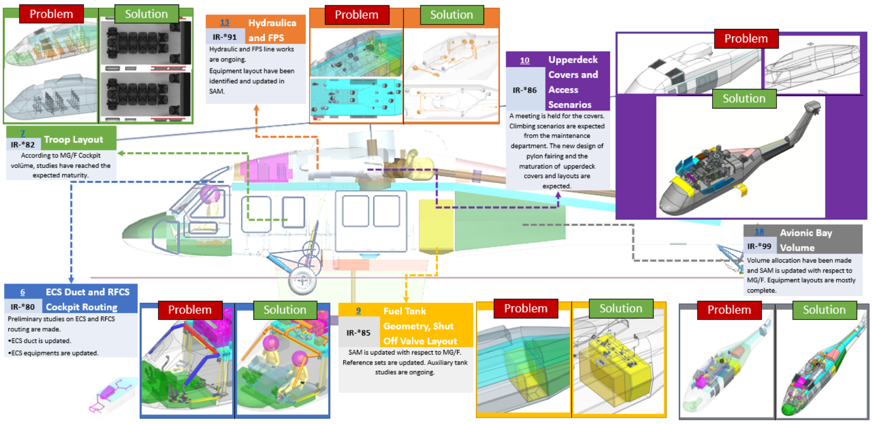


Figure 14 DMU problem and solution view scheme

3.5. DMU review reports

DMU Team is responsible for creating DMU Review Report documents. There are 2 different type documents for DMU review report;

- Certification DMU Review Report: The purpose of this document is to show compliance with relevant CS 29 requirements that needs DMU Review, in each ATA chapters' Certification Plan of Helicopters. This document is created by DMU team and system design engineer, published by DMU team.
- Qualification DMU Review Report: The purpose of this document is to show SIRD compliance with requirements that needs to be verified by DMU Review, in each ATA Chapters for a Helicopter. This document is created and published by DMU team.

Following contents must be included in DMU review report as also shown at figure 15;

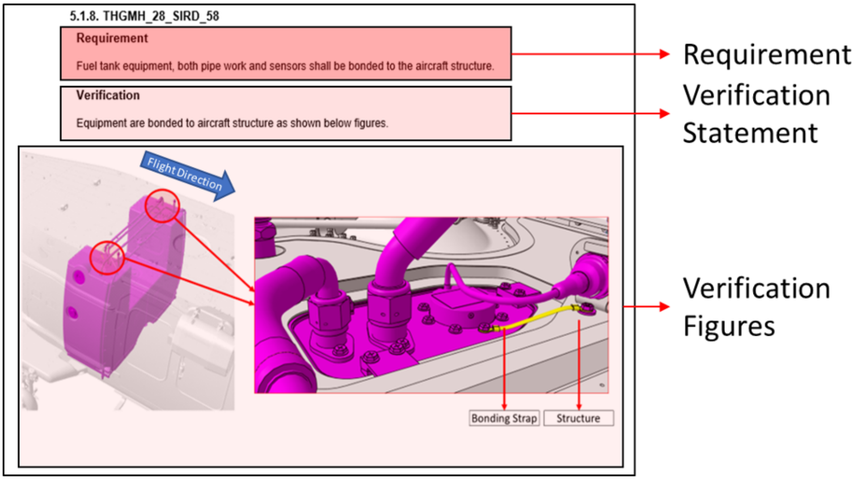


Figure 15 DMU Review Report sample for helicopter fuel requiement

- Requirement
- Verification Statement
- Verification Figures
- General view of helicopter with equipment
- Flight direction
- Detail view of parts
- Name of detail parts

These documents provide to proof of concept which is an engineering evolution.

4. Conclusion

Digital Mock-Up (DMU) serves as a highly effective tool for stakeholders to collaborate on product development and integration, centered around a common objective of creating competitive products. By providing a virtual representation of a product, DMU enables various teams—such as design, engineering, manufacturing, and marketing—to work together seamlessly, ensuring that all aspects of the product are considered from the outset. This collaborative approach not only fosters innovation but also helps to identify potential issues early in the development process, ultimately leading to a more refined and market-ready product.

Looking ahead, the future integration of DMU with other advanced technologies, such as artificial intelligence, machine learning, and augmented reality, will be crucial in enhancing its capabilities. As DMU evolves into a central component of broader product lifecycle strategies, it will play a pivotal role in streamlining processes from initial concept through to production and beyond. The advancement of technology facilitates the overcoming of barriers related to collaboration and communication needs and objectives, allowing teams to share insights and feedback in real-time, regardless of geographical location.

However, a significant challenge for DMU lies in its ability to effectively integrate these emerging technologies to enhance the design and review processes. The integration of real-time design technologies can generate valuable design information during the development phase, enabling teams to make informed decisions quickly. Furthermore, collaborative sessions can bridge gaps through subsequent design reviews, allowing for both review and design to occur simultaneously. This iterative process not only accelerates the development timeline but also ensures that all stakeholder perspectives are considered, leading to a more comprehensive and successful product.

As DMU continues to evolve, it has the potential to become a widely adopted tool in complex product development systems globally. Its ability to enhance efficiency and collaboration will be invaluable, not only for major innovations but also for smaller improvements that can significantly impact a company's competitive edge. By leveraging DMU effectively, organizations can optimize their product development processes, reduce time-to-market, and ultimately deliver higher-quality products that meet the ever-changing demands of consumers. In this way, DMU stands to transform the landscape of product development, making it more agile, responsive, and aligned with market needs.

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