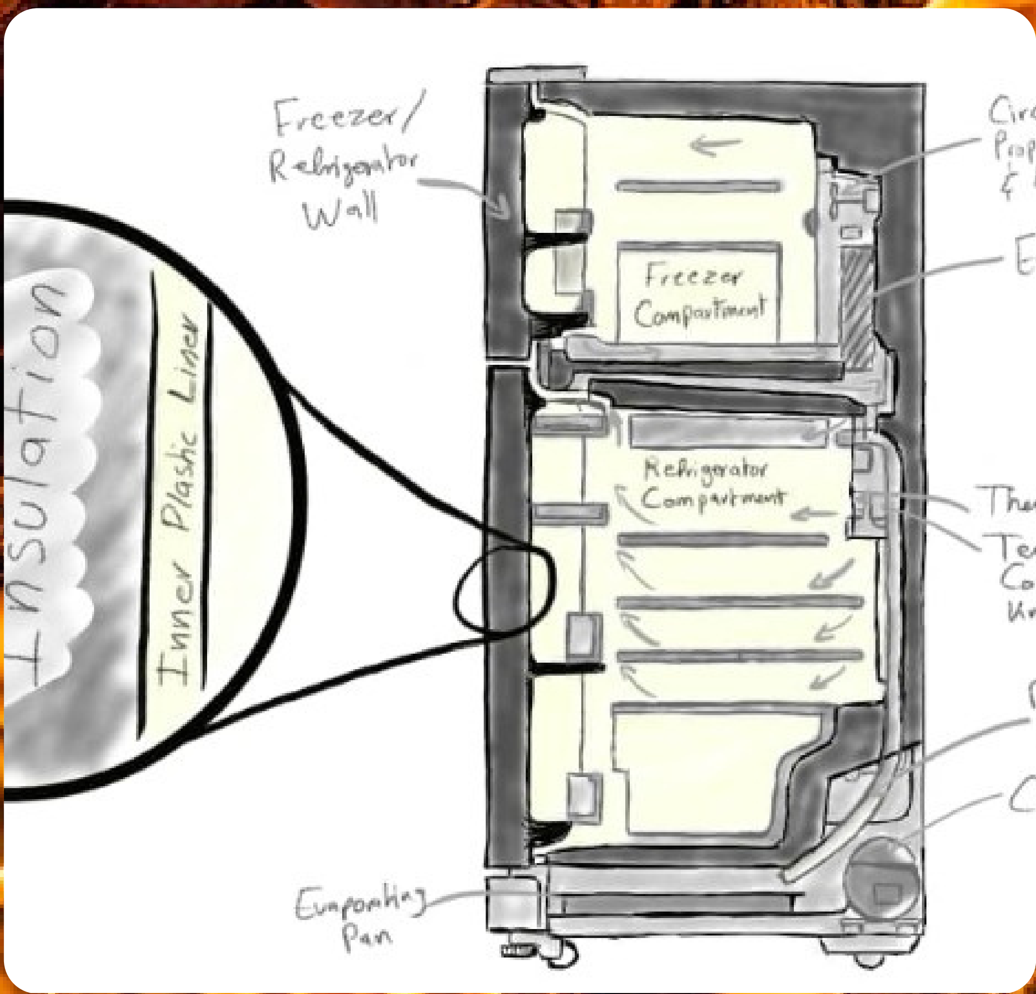
UTM UNIVERSITI TEKNOLOGI MALAYSIA

HEAT TRASFER

Comparison of Insulation Materials



Mazen Omar Mohamed

Matric No: A20EM4015

Table of Contents

Introduction

The 21st century technological revolution has brought about many electronic appliances for the every-day consumer. Be it refrigerators, freezers, or even air conditioners. However, all these devices and gadgets have something in common, as they require some form of thermal insulation in order to maintain their operation and to prevent unnecessary heat transfer to the surroundings. Within domestic appliances, refrigerator systems have some of the largest portions of energy consumption; Hence, to increase energy efficiency and reduce energy consumption, a great effort is made in selecting the optimum thickness and insulation materials for the refrigerator walls as suggested in (DEMİR, 2018, p.1).

Problem Statement:

This particular case study focuses on comparing the insulation materials currently used in refrigerator systems in terms of energy efficiency, as well as the economical and environmental impact of the insulation materials regarding their sustainability of use in the industry. The scope of the study pertains to the four types of insulation materials readily used in refrigerators. These materials include Polyurethane foam (PU foam), a type of flexible polymer fitted into the walls. Vacuum Insulated Panels (VIP) which are vacuum sealed plates, enclosed around a rigid core made from various insulation materials. In this study, the VIP's to be compared have cores made from fumed silica, glass fiber and other alternate materials.
The thermal properties and costs of each material to be used as insulation is tabulated in table 1, as shown below.

Insulation material	Identifier	Initial thermal conductivity (W/mK)	Density (kg/m^3)	Cost (£/m^3)
PU Foam	M1	0.0215	80	950
Fumed silica VIP	M2	0.0037	200	2390
Glass fibre VIP	M3	0.0029	250	1800
Alternate core VIP	M4	0.0076	220	2000

Table 1. Insulation Materials and properties [2]

System Description

To compare and contrast between the insulation materials selected above, the system to be analyzed in this study will be a domestic refrigerator commonly used in households. The analysis approach and methodology will be discussed in the following sections. The schematic of the system is as shown below.

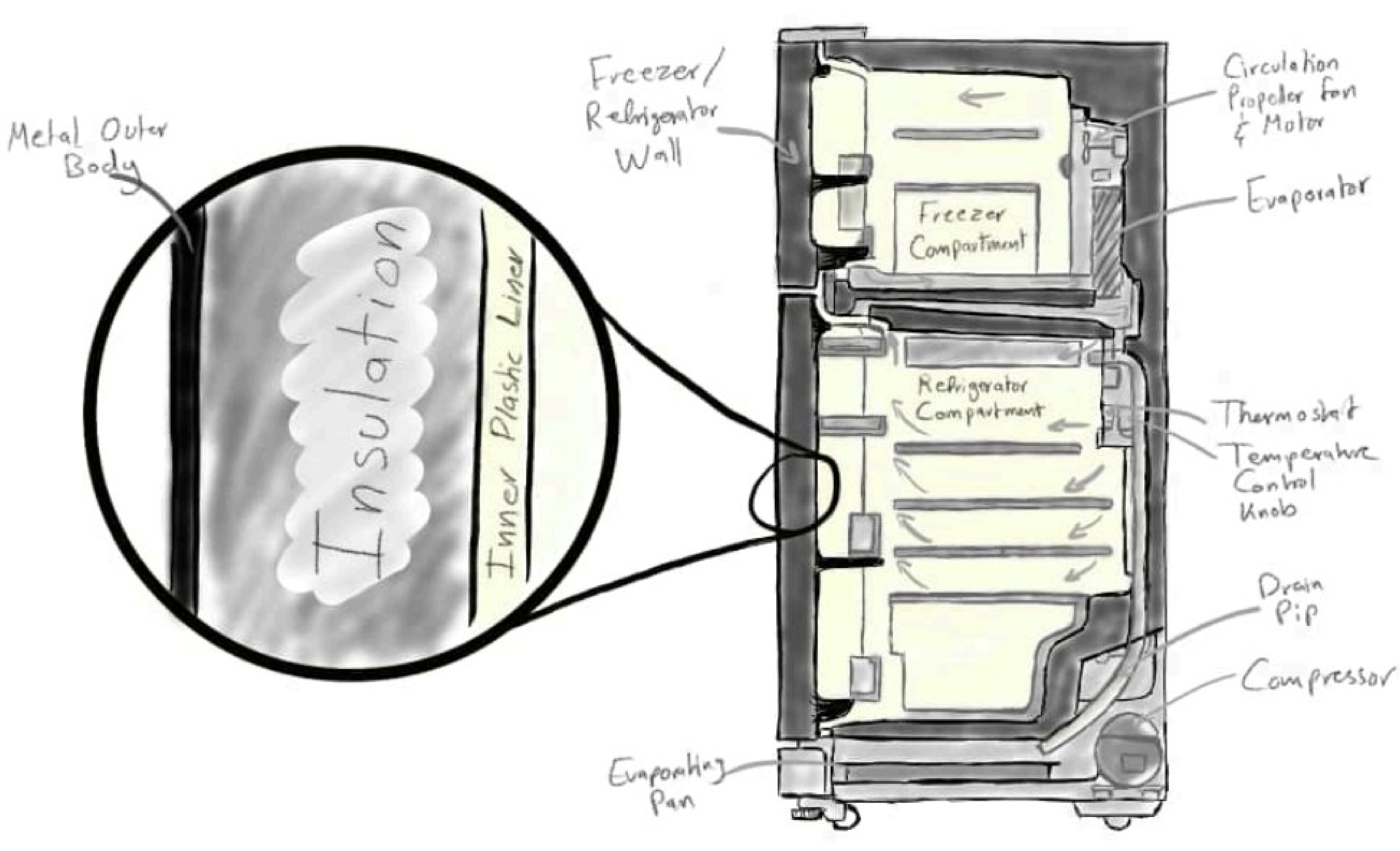


Fig 1. System Schematic Sketch

To compare the insulation materials in uniform conditions, the thermal properties of the outermost layer of metal and the innermost plastic layer are assumed to be constant. The only variable thermal resistance in the system are the materials to be substituted into the section labeled as "Insulation" in schematic shown above. The heat transfer coefficient for the inner and outer walls, along with the temperature at the surfaces can be seen tabulated in table 2.

	Heat transfer coefficient W/m^2K	Temperature (°C)
Inner walls — Fridge	1.3	5
Inner walls — Freezer	1.3	-20
Outer walls	1.3	25

Table 2. Heat Transfer Coefficient and Temperature for various surfaces [2]

However, for a given refrigerator volume, insulation materials are not always used in equal amounts. Instead, for a system, the optimization of insulation thickness is pivotal in improving performances for domestic refrigerators as suggested by (Yoon et al., 2013, p.1). Hence, while it is fair to conduct the heat transfer analysis with constant thickness for each insulation material, it is not at all realistic or feasible in application.

As such, it is far more practical to compare the insulation materials using their optimal thickness instead of a constant arbitrary constant thickness value. Nevertheless, in the interest of unbiased and ethical comparison, both ideas of implementation will be tested and reviewed using identical methodologies of analysis.

The analysis of optimum thickness on each material was carried out using a parametric study 3D-plot comparing the cost for each material with the fridge and freezer thickness required is illustrated in **Fig 2** below.

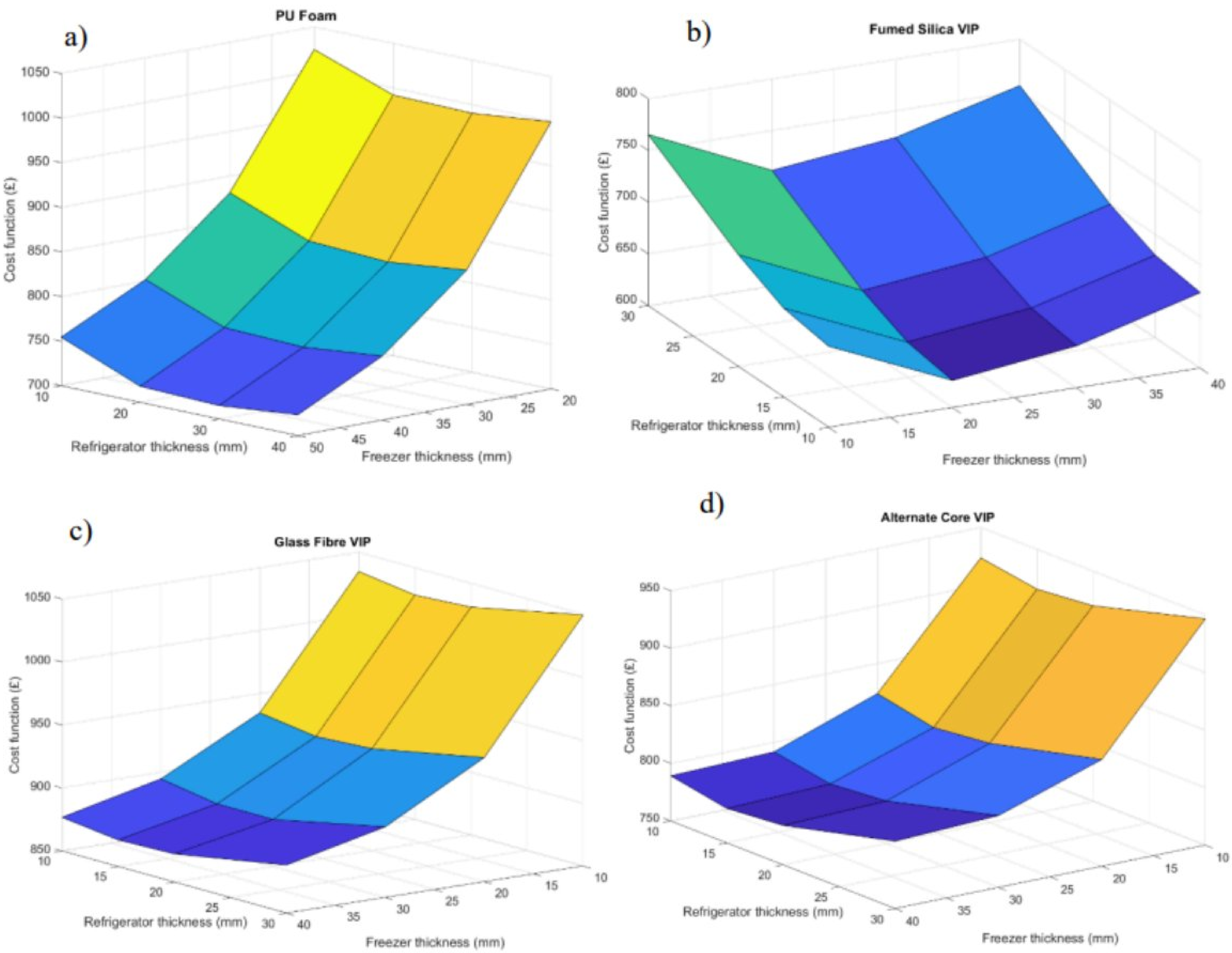


Fig 2. Parametric thickness optimisation surface for a) PU foam b) Fumed silica VIP c) Glass fibre VIP d) Alternate core VIP [2]

The resulting optimal thickness for each material as well as its effects on carbon footprint and cost suggested by (Verma & Singh, 2020) is tabulated in table 3 below.

	Fridge insulation thickness (t_{fridge})	Freezer insulation thickness ($t_{freezer}$)	Lifetime energy consumption {% change} (kWh)	Cost function (£)	CO_2e emissions (kg)	Weight of insulation (kg)	Inner volume (l)
M1	30	50	3802.72 {0}	715.14	1168.2	24.72	450
M2	10	20	3057.62 {19.6}	626.32	939.3	27.2	598
M3	15	40	4418.38 {-16.2}	871.14	1357.3	44.28	527
M4	15	40	3405.41 {10.4}	779.94	1046.1	38.96	527

Table 3. Optimized thickness of insulation materials and its relative effects [2]

The insulation materials in the figure above can be identified by their unique identifier as previously listed in table 1. The insulation thickness referenced in the table for fridge and freezer insulation above refers to thickness in (mm).

Analysis of Heat Transfer

In this section, a sample of cross sectional area $1m^2$ will be analyzed to showcase the performance of different insulating materials. The analysis will be carried out using a predetermined arbitrary thickness of 3mm as well as each material's respective optimal thickness.

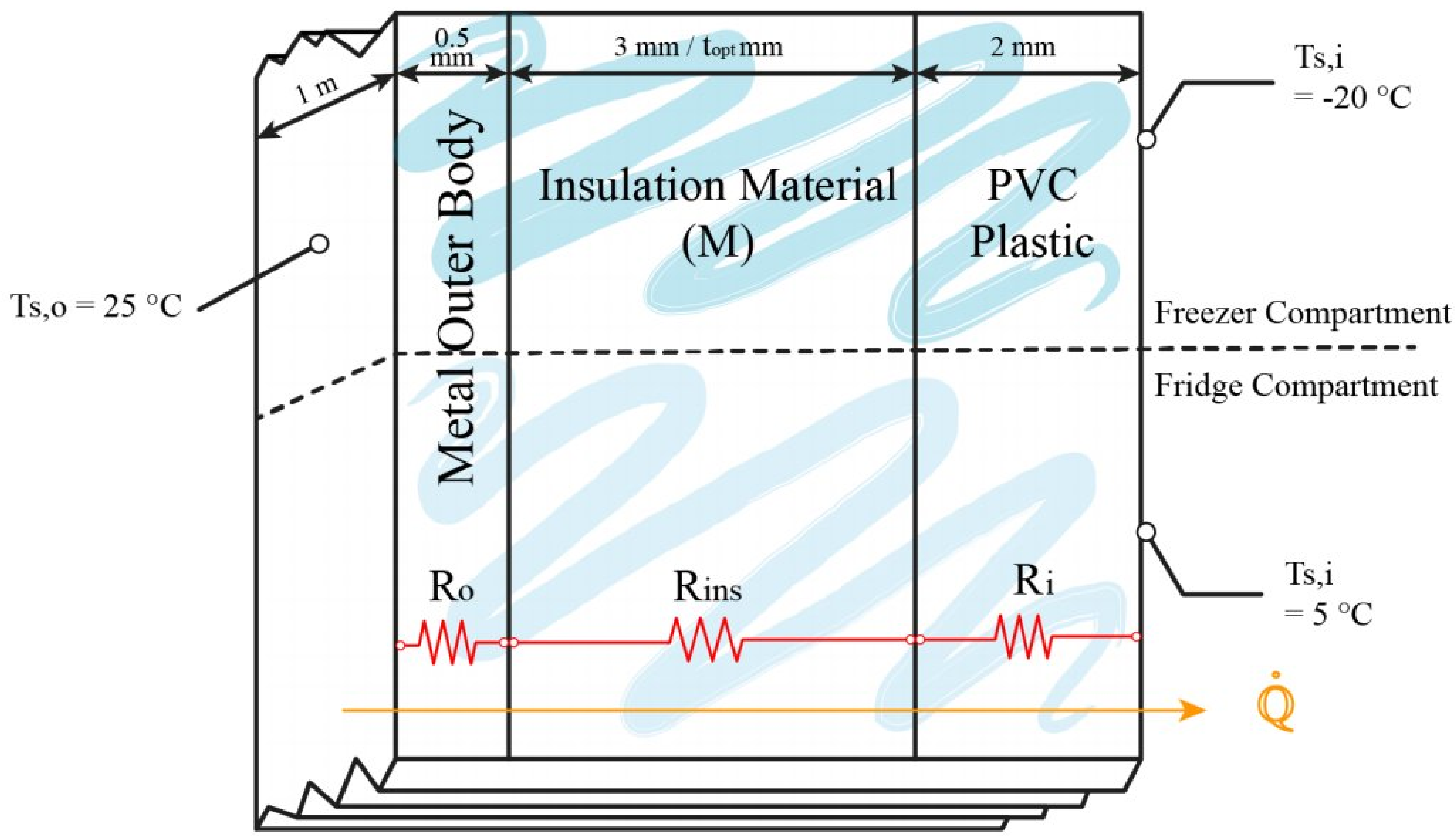


Figure 3. Labeled Schematic Diagram of 1mx1m refrigerator wall cross section.

Methodology

The performance of each insulating material will be compared according to the rate of heat transfer that it allows under the conditions shown in Figure 3. For a refrigerator, the amount of heat gain from the kitchen environment (at 25C) to the chilled environment (at 5 ºC in the fridge and -20 ºC in the freezer) must be minimized to achieve maximum refrigeration efficiency; decreasing the workload on the compressor and ultimately being environmentally sustainable. Therefore, the best insulating material is the one that results in the lowest rate of heat transfer.

The approach used by the *Heat and Mass Transfer textbook by Y.A. Cengal & A.J. Ghajar* to calculate the rate of heat transfer utilizes the concept of a thermal resistance circuit as shown in Figure 3; which will be used in this analysis. After obtaining the total resistance of the circuit; the following equation can be used to get the rate of heat transfer across its length, L.

$$\dot{Q}_{\text{cond, wall}} = \frac{T_1 - T_2}{R_{\text{wall}}} \quad \text{(W)}$$

Formula 1. Rate of Heat Transfer formula where T1 and T2 are the temperatures of the outer and inner surroundings respectively [4].

Heat will have to pass through convection across the outer surrounding (kitchen), followed by conduction through the 3 layers of the refrigerator's wall, then to the inner surrounding (chilled space). However, calculating the convection parts of the heat transfer has proven to be irrelevant to our study and does not serve the purpose of this analysis, since the convection resistance is kept constant while comparing all the insulating materials. The following formula is used to calculate the conductive resistance through the layers of the refrigerator wall.

$$R_{\text{wall}} = \frac{L}{kA} \quad \text{(K/W)}$$

Formula 2. Conduction Thermal Resistance formula

The sum of all thermal resistances is the total thermal resistance that will be used in Formula 1. The conductivity constants, k, of the metal outer body and the freezer and fridge PVC inner lining are all kept constant throughout the analysis (control), while only the conductivity constant of the insulating material is varied according to its type.

Assumptions

- Heat transfer due to radiation is neglected.
- Perfect thermal contact between layers (no air gap).
- Insulating material is ideal.
- Heat transfer coefficient is constant across the entire thickness.
- Steady state.
- Compressor and Evaporator walls are neglected.
- All layers of the refrigerator wall are isothermal.
- Inner and outer surface temperatures are assumed to be the same as their respective surrounding temperatures.

Analysis

Referring to formula 2, the thermal resistance is inversely proportional to the thermal conductivity of the material, while it is directly proportional to the thickness of the layer, L. Meaning, the thicker the insulation material layer is, the less heat that can transfer to the chilled space, which means the compressors do not have to consume more energy to maintain the temperature of the compartments. However, increasing the insulation layer thickness results in more material being used; which increases the cost of production. The ratio of improved insulation due to larger thickness to the increase in cost is considered by the calculated optimal thicknesses of each material. Thus, it is more realistic to compare the materials according to their optimal thickness, since some insulating materials might be better if provided in the same thickness as others but drive the cost high significantly, rendering it unfeasible. This is proven by glass fiber VIP as shown in table 3; where it has the lowest thermal conductivity of 0.0029 $W/m^2.k$ while scoring the highest cost function. In addition, another relation between the insulating material used is the CO2 emission; which directly affects the sustainability of their usage.

Results

In this section, the results of all the calculations of each layer's thermal resistance and the final rate of heat transfer to the freezer and fridge compartments using the 4 different insulating materials (refer to **table 1**) will be tabulated and briefed. Each material's optimal thickness (refer to **table 3**) will be used first to compare their best performance. Then, for the sake of consistency, a predetermined thickness of 3 mm will be used for all insulating material layers. The tabulated conductivity coefficients of the freezer and fridge walls shown in **table 2** are first used to calculate the individual thermal resistances of each layer.

The following figure shows a sample calculation of convection and conduction thermal resistance using their respective formulas.

$$Ri = \frac{L}{k\,As} = \frac{3\times10^{-3}}{1.3 \times 1} = 2.308 \times 10^{-3}$$

The cross-sectional area is set to be 1 m^2 to simplify the calculation.

The following table shows the **constant** thermal resistances of the outer metal body and the inner PVC shell:

Name	Thermal Resistance
Ri	2.31E-03
Ro (Fridge & Freezer)	7.69E-04

Table 4. Control results for thermal resistance of the metal outer body and the PVC plastic inner liner.

Optimal Thickness

The conductive thermal resistance of all the materials are tabulated in the following table.

M	R material	k (W/m.k)	t,opt (mm)		Thermal Resistance (k/W)	
			Fridge	Freezer	Fridge	Freezer
1	PU Foam	0.0215	30	50	1.3953	2.3256
2	Fumed Silica VIP	0.0037	10	20	2.7027	5.4054
3	Glass Fiber VIP	0.0029	15	40	5.1724	13.7931
4	Alternate Core VIP	0.0076	15	40	1.9737	5.2632

Table 5. Conductive thermal resistance results for the fridge and freezer of each material using their optimal thicknesses.

Using the results in table 5 and table 4, formula 1 will be used to calculate the rate of heat transfer that each material allows. The total resistance for each case (material) is first calculated, then input into the formula.

M	R material	Total Thermal Resistance, Rtot=Ri+Rmaterial+Ri (k/W)		Rate of Heat Loss (W)		Price Estimation (RM/m^2)
		Fridge	Freezer	Fridge	Freezer	
1	PU Foam	1.3984	2.3287	14.3018	19.3244	5650.61
2	Fumed Silica VIP	2.7058	5.4085	7.3916	8.3203	14215.74
3	Glass Fiber VIP	5.1755	13.7962	3.8644	3.2618	10706.41
4	Alternate Core VIP	1.9768	5.2662	10.1176	8.5450	11896.01

Table 6. Rate of heat transfer results for each material through the fridge and freezer.

As shown in table 6; the highest rate of heat transfer among the four materials is the PU Foam, while the lowest appears to be the Glass Fiber VIP (Vacuum Insulated Panel).

Constant Thickness

The arbitrary thickness chosen to be used across all materials is 3 mm. This part will follow the same process as with the optimal thickness.

The following shows the tabulated thermal resistances of each material at constant thickness.

M	R material	k (W/m.k)	Thermal Resistance (k/W)
1	PU Foam	0.0215	0.1395
2	Fumed Silica VIP	0.0037	0.8108
3	Glass Fiber VIP	0.0029	1.0345
4	Alternate Core VIP	0.0076	0.3947

Table 7. Conductive thermal resistance results of each material at 3 mm of thickness.

Moreover, similar to the previous section, the rate of heat transfer is calculated using the data from table 7, table 4 and formula 1.

M	R material	Thermal Resistance (k/W)	Total Thermal Resistance, Rtot=Ri+Rmaterial+Ri (k/W)	Rate of Heat Loss (W)	
				Fridge	Freezer
1	PU Foam	0.1395	0.1426	140.2408	315.5419
2	Fumed Silica VIP	0.8108	0.8139	24.5734	55.2902
3	Glass Fiber VIP	1.0345	1.0376	19.2760	43.3710
4	Alternate Core VIP	0.3947	0.3978	50.2748	113.1183

Table 8. Rate of heat transfer results for each material using constant thickness of 3 mm.

The rate of heat transfer results follow the same trend observed with the optimal thickness. However, there are noticeable differences in the results of Fumed Silica and Alternate Core VIP materials using their optimal thicknesses versus a constant thickness. The following section of this report will discuss all the results obtained and relate them to the objective of this study: the sustainability of using each material; thus ultimately selecting the best one.

Discussion

Based on the above results obtained from the evaluation of different insulation materials for fridge and freezer applications provide valuable insights regarding their thermal resistance, rate of heat loss, and cost. Based on the data, Glass Fiber VIP demonstrates the highest thermal resistance among the tested materials, followed by Fumed Silica VIP, Alternate Core VIP, and PU Foam. In terms of the rate of heat loss, PU Foam performs best for both the fridge and freezer, followed by Alternate Core VIP, Fumed Silica VIP, and Glass Fiber VIP. Regarding cost, Fumed Silica VIP is the most expensive option, followed by Alternate Core VIP, Glass Fiber VIP, and PU Foam.

The aforementioned findings lead to a conclusive determination that Glass Fiber VIP emerges as the most efficient choice for insulation owing to its commendable thermal resistance and minimal heat loss rate.

However, it is vital to recognize that considerations beyond thermal efficiency should accompany our selection process for an insulation material. Additional factors encompass ecological aspects regarding its production ease and viability alongside market availability for practical implementation purposes.

Scrutinizing Glass Fiber VIP from an eco-friendly perspective necessitates a diligent evaluation of its overall environmental impact encompassing both manufacturing and installation processes where inadvertent release of airborne particles may pose potential health risks.

Moreover it is imperative to assess the feasibility and efficiency of producing Glass Fiber VIP while factoring in market accessibility constraints. Any challenges associated with manufacturing or sourcing might impede its applicability or hinder widespread adoption.

Sustainability serves as yet another pivotal aspect warranting thorough examination before opting for Glass Fiber VIP as an insulation material. A comprehensive analysis focusing on energy efficiency, recyclability, and overall environmental impact towards achieving long term sustainability should guide our decision making process.

Consequently relying on further research initiatives along with consultative inputs from domain experts are highly recommended. A holistic approach considering thermal efficiency, eco-friendliness availability, sustainability, and cost effectiveness paves way for well informed decision making aligning with our desired objectives.

In summary, while Glass Fiber VIP appears to be the most efficient insulation material based on the current results, a thorough assessment of other influencing factors is necessary before finalizing the choice. This will ensure that the selected material meets the requirements of thermal efficiency, environmental impact, availability, and sustainability, resulting in an optimal and well-informed decision.

Sustainability:

Refrigerators justify their existence by performing their primary task of maintaining specific temperature requirements vital for preserving fresh foods while keeping energy consumption at an optimum level—a feat made possible through seamless insulation applications integrated within fridge walls and body structures that help minimize heat infiltration from external sources. This piece aims to scrutinize various insulation materials' suitability measures with respect to sustainability and Thermal Resistance values employed in low-temperature appliance operations. Simply put, the Heat Resistance factor measures an insulating material's potency in blocking thermal exchange with higher values indicating superior performance levels. To this effect, popularly used refrigerator insulation options include Polyurethane foam (PUF) and Expanded Polystyrene Foam (EPS). The former offers impressive results attributed to its closed-cell structure that significantly resists heat transfer due to reduced conductivity levels while efficiently taking care of any possible environmental interference with high efficiency rates like moisture or light sources. Although EPS succeeds as a good insulator by trapping air within its expanded structure, its thermal resistance value does not reach the same level of excellence PUF offers.

When considering sustainability, it is important to evaluate the environmental impact of insulation materials, especially in low-temperature applications where energy efficiency is crucial. Polyurethane foam, although highly effective in terms of thermal resistance, has environmental concerns. Its production involves the use of chemicals, including volatile organic compounds (VOCs), and some blowing agents with high global warming potential (GWP). The disposal of polyurethane foam can also be challenging as it is not easily recyclable.

On the other hand, EPS foam is more environmentally friendly. It is made from expandable polystyrene beads and can be recycled. EPS foam has a lower GWP and a reduced impact on ozone depletion compared to other insulation materials. Its manufacturing process also consumes less energy, making it a sustainable choice. Additionally, EPS foam can be easily shaped to fit specific areas within the fridge, providing a tight and effective insulation barrier.

Besides polyurethane foam and EPS foam, other sustainable insulation options are emerging in the market. For instance, natural fiber-based insulation materials, such as sheep's wool or cellulose, are gaining popularity. These materials offer good thermal resistance and are renewable, biodegradable, and non-toxic. However, their use in fridge insulation is still limited due to the need for further research and development to ensure their compatibility with low-temperature environments and potential moisture issues.

In conclusion, while polyurethane foam provides excellent thermal resistance, its sustainability for low-temperature applications in fridges raises concerns. On the other hand, EPS foam offers a balance between thermal resistance and environmental impact, as it is recyclable and has a lower GWP. Exploring alternative insulation materials, such as natural fiber-based options, holds promise for more sustainable refrigeration systems. Striking a balance between thermal performance, energy efficiency, and environmental impact is essential for developing insulation materials that meet the demands of low-temperature applications in fridges.

We will compare two types of insulation materials: Fumed Silica Vacuum Insulation Panels (VIP) and Glass Fiber VIP, focusing on their thermal resistance and sustainability for low-temperature applications within a fridge. Additionally, we will explore if there are any better alternative insulation options available.

Thermal resistance is a key factor in evaluating the effectiveness of insulation materials. Fumed Silica VIPs offer excellent thermal resistance due to the vacuum-sealed panel, which significantly reduces heat conduction. Fumed silica, a highly insulating material with a nonporous structure, has low thermal conductivity, making it an efficient barrier against heat transfer. This results in superior insulation performance, minimizing the amount of heat transferred inside the fridge.

Glass Fiber VIPs, on the other hand, also provide good thermal resistance. Glass fibers have a low thermal conductivity, which aids in reducing heat transfer. The vacuum-sealed panel further enhances the insulation performance by minimizing heat conduction through the fibers. While glass fiber VIPs may have slightly lower thermal resistance compared to fumed silica VIPs, they still offer significant insulation benefits.

Achieving sustainability goals demands that we acknowledge and mitigate any negative effects that various insulation materials may pose for our planet. If these effects go unchecked and are particularly troublesome in cases involving low temperatures—when energy conservation initiatives are vital—the situation only worsens. Fumed Silica VIPs have several sustainability advantages. Fumed silica is an inert and non-toxic material, and its production involves minimal environmental impact. However, the manufacturing process of Fumed Silica VIPs may include the use of chemical binders or sealants, which may affect their overall sustainability.

Glass Fiber VIPs also have sustainability benefits. Glass fibers are made from natural materials, such as sand, and are considered non-toxic and non-hazardous. They can be recycled and have a longer lifespan compared to some other insulation materials. Additionally, the manufacturing process for glass fiber VIPs involves less energy consumption and has a lower environmental impact compared to certain alternatives.

It is undeniable that Fumed Silica VIPs and Glass Fiber VIPs provide superior performance when utilized as wall insulation in refrigerator appliances due to their durability against heat coupled with commendable environmental safety standards. Yet It would be prudent to consider other alternatives lined up against these types of insulators such as Aerogel or Natural Fibre based material specifically curated for low temperature applications which seem increasingly promising over time. Among the established alternative insulating products that showcase excellent features within this category include the lightweighted Aerogel with remarkable ability in providing premium insulative properties due to its exceptional high thermal resistance. Additionally we also have Natural Fiber based materials such as sheep wool or cellulose offering sustainable properties plus biodegradable and non toxic features with an ability to retain heat.

Fumed Silica VIP offers several advantages. It has excellent thermal resistance due to its nonporous structure and low thermal conductivity. Fumed silica provides superior insulation performance, effectively minimizing heat transfer. Additionally, fumed silica is an inert and non-toxic material, making it environmentally friendly. However, the manufacturing process may involve the use of chemical binders or sealants, which can impact overall sustainability.

Glass Fiber VIP offers great thermal resistance - even though it's slightly lower than fumed silica - among other benefits. One of the ways in which glass fibers help maintain insulation is through their low thermal conductivity properties that minimize heat transfer inside structures or equipment where they're used. Thanks to using natural resources like sand and producing them without hazardous materials, these fibers are safe for individuals handling them and the environment at large. Moreover, their sustainable manufacturing process denotes considerably less energy usage compared to some other alternatives on the market.

Considering these factors, the choice between Fumed Silica VIP and Glass Fiber VIP depends on specific needs. If high thermal resistance is the primary concern, fumed silica may be a better option. On the other hand, if sustainability and recyclability are key considerations, glass fiber VIPs offer advantages.

Apart from Fumed Silica VIP and Glass Fiber VIP, there are alternative insulation options available for low-temperature applications:

Aerogel: Aerogel is an ultra-lightweight material with exceptional insulating properties. It has high thermal resistance and effectively prevents heat transfer. Aerogel is also environmentally friendly and can be a suitable alternative to consider.

Natural Fiber-based Insulation: Materials such as sheep's wool or cellulose offer renewable, biodegradable, and non-toxic insulation options. These natural fibers provide good thermal resistance and can be environmentally sustainable choices.

The selection of the best insulation material depends on a comprehensive evaluation of specific requirements, including thermal performance, sustainability goals, and cost considerations. Conducting a detailed analysis of these factors will help determine the most suitable insulation material for low-temperature applications in fridges.

In achieving optimal thermal efficiency while conserving energy across an array of applications-including refrigeration-the role played by appropriate insulation materials is pivotal. One widely utilized choice for insulation purposes is Vacuum Insulated Panels (VIP), that excel at limiting heat flow while exhibiting superior thermal resistance capabilities.

VIPs consist of a core material enclosed in an airtight barrier. The core material typically comprises a rigid foam or powder insulation, and the air is removed from the panel, creating a vacuum. The absence of air eliminates conduction and convection, making VIPs highly effective in reducing heat transfer. The airtight barrier further prevents the infiltration of gasses that could compromise the insulation's performance.

When it comes to refrigerators, VIPs can be used in two main areas: the walls of the fridge and the body of the fridge. In the walls, VIPs are typically incorporated as a layer between the inner and outer panels. This placement ensures minimal heat transfer from the external environment to the interior of the refrigerator. For the body of the fridge, VIPs can be used to insulate the internal compartment, maintaining the desired low temperatures efficiently.

Compared to other insulation materials, VIPs offer excellent thermal resistance. Their high insulation performance allows for thinner insulation layers, resulting in increased interior space utilization in appliances like refrigerators. In terms of sustainability, VIPs have some advantages. They are often made from non-toxic materials, such as fiberglass or silica, which are recyclable. Additionally, the long lifespan of VIPs reduces the need for frequent replacement, contributing to their sustainability.

However, VIPs do have some drawbacks. They can be relatively expensive compared to traditional insulation materials like expanded polystyrene (EPS) or polyurethane foam. The initial cost of VIPs may be a barrier for widespread adoption, especially in cost-sensitive applications. Additionally, the vacuum-sealed nature of VIPs makes them susceptible to damage from punctures or impacts, which could compromise their insulation properties. This fragility requires careful handling and installation.

Regarding alternatives to VIPs, some emerging insulation materials show promise in terms of cost and sustainability. One such alternative is aerogel insulation, which consists of a nanoporous material with extremely low density. Aerogels offer excellent thermal resistance and can be more durable than VIPs, but they can still be relatively expensive.

Polyurethane foam insulation is another feasible alternative worth considering today thanks to its technological advancements in formulation and production techniques that now provide better thermal efficiency but at an affordable price range. It has excellent insulating properties making it a popular choice material for refrigeration equipment. That said, when selecting an insulation material.

Some essential environmental issues must be considered like the impact on global warming potential (GWP) and ozone depletion potential (ODP). Various materials such as HFCs or CFCs used in insulation contribute to greenhouse gas emissions or damage the ozone layer leading to catastrophic consequences. Choosing low GWP and ODP materials like VIPs or environmentally friendly polyurethane foams helps mitigate these environmental risks.

To sum up. Vacuum Insulated Panels (VIP) prove effective insulation materials frequently incorporated in refrigeration units for their remarkable thermal resistance capabilities that can work in both the walls and body of refrigerators. Although they offer several benefits towards better sustainability practices and thermal performance their shortcomings like fragile components alongside costly pricing remain limiting factors which can be solved by relying on alternatives like aerogel insulation or upgraded polyurethane foam offering cost effective sustainable options. It's therefore important to consider aspects like affordability, eco-friendliness and environmental impacts while prioritizing on critical aspects related to the thermal resistivity of any insulating material opted.

Conclusion

To summarize,, taking into account the efficacy and economical factors affecting the sample data, it is evident from the peer reviewed studies and the experimental data above, that the leading solution for thermal insulation in refrigerators are Glass-Fibre VIPs (Vaccum Insulated Panel). However, recounting the sustainability issues surrounding VIP's that mainly conform to high cost and low wear resistance, in the context of cost effective application, VIP's may not be the solution desired by the consumer.

In contrast, alternative thermal insulation materials such as PU Foam might seem outdated but they do provide good thermal performance at the cost of sustainability, This discrepancy is largely due to the manufacturing processes and materials used to produce PU foam, which contributes huge amounts to waste dumping and water pollution worldwide

Analyzing the data presented in this case study, the only conclusive determination highlights Glass-Fibre VIP's as the leading solution to effective and ecological thermal insulation, but at an excessive cost that might prove to be unsustainable within the global rapid manufacturing industry looking to turn quick profits with automated production at its forefront.

References

1. DEMİR, H. (2018). Determination of optimum insulation thickness distribution for refrigerators. *Süleyman Demirel Üniversitesi Fen Bilimleri Enstitüsü Dergisi*, *22*(1), 126. https://doi.org/10.19113/sdufbed.56037

2. Verma, S., & Singh, H. (2020, April). *Why and Which Insulation Materials for Refrigerators!* [Paper presentation] 25th IIR International Congress of Refrigeration, Montreal, Canada.

3. Yoon, W. J., Seo, K., & Kim, Y. (2013). Development of an optimization strategy for insulation thickness of a domestic refrigerator-freezer. *International Journal of Refrigeration*, *36*(3), 1162-1172. https://doi.org/10.1016/j.ijrefrig.2012.11.013

4. Cengel, Y. A., & Ghajar, A. J. (2015, April 4). *Heat and Mass Transfer: Fundamentals and Applications* (5th ed.), 157-175.

5. Barrow, C. (2006). *Environmental management for sustainable development*. Routledge.

Appendix

Table 1.

Insulation material	Identifier	Initial thermal conductivity (W/mK)	Density (kg/m^3)	Cost (£/m^3)
PU Foam	M1	0.0215	80	950
Fumed silica VIP	M2	0.0037	200	2390
Glass fibre VIP	M3	0.0029	250	1800
Alternate core VIP	M4	0.0076	220	2000

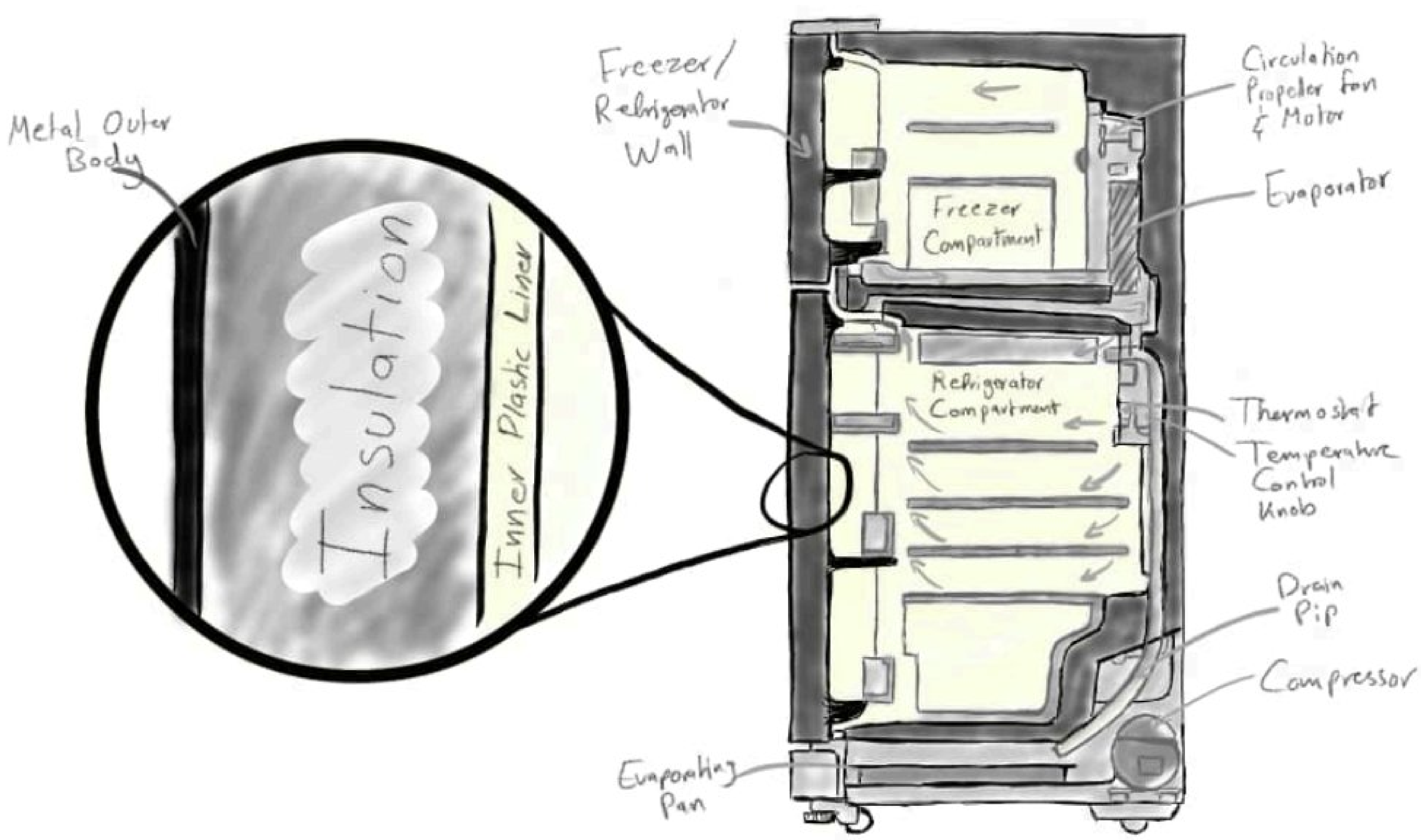


Fig 1.

	Heat transfer coefficient W/m^{2}K	Temperature (°C)
Inner walls — Fridge	1.3	5
Inner walls — Freezer	1.3	-20
Outer walls	1.3	25

Table 2.

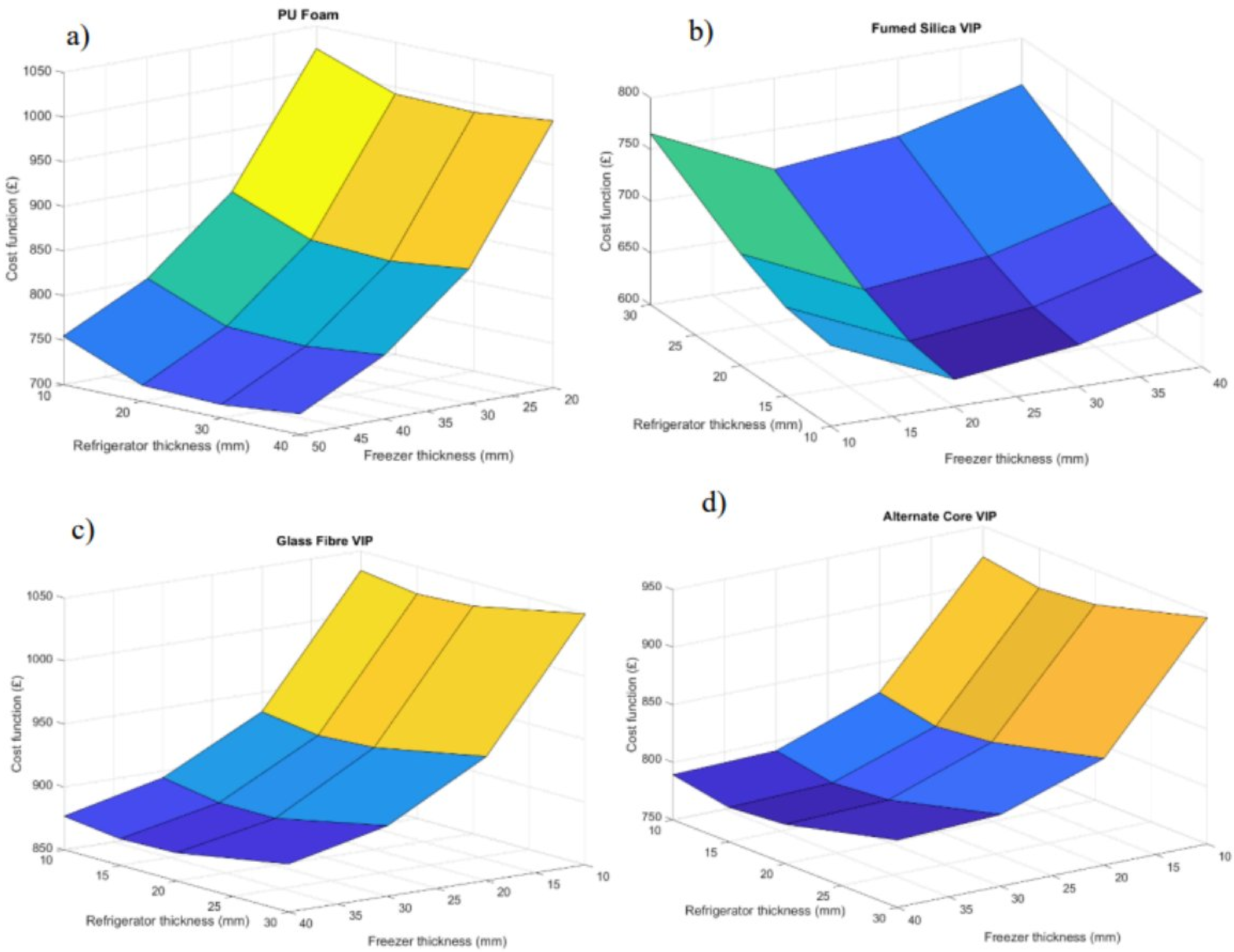


Fig 2.

	Fridge insulation thickness (t_{fridge})	Freezer insulation thickness ($t_{freezer}$)	Lifetime energy consumption {% change} (kWh)	Cost function (£)	CO_2e emissions (kg)	Weight of insulation (kg)	Inner volume (l)
M1	30	50	3802.72 {0}	715.14	1168.2	24.72	450
M2	10	20	3057.62 {19.6}	626.32	939.3	27.2	598
M3	15	40	4418.38 {-16.2}	871.14	1357.3	44.28	527
M4	15	40	3405.41 {10.4}	779.94	1046.1	38.96	527

Table 3.

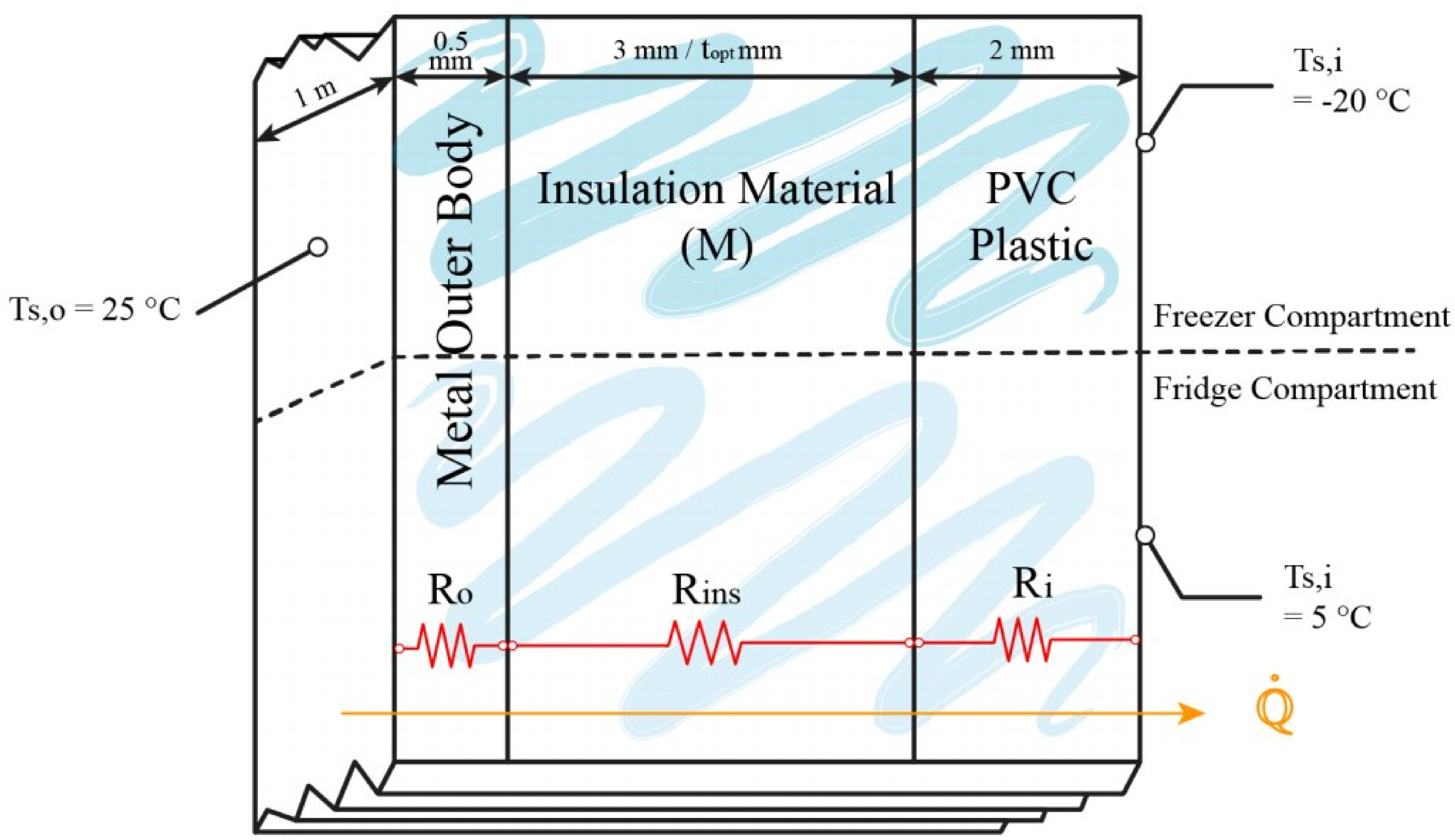


Fig 3.

Name	Thermal Resistance
Ri	2.31E-03
Ro (Fridge & Freezer)	7.69E-04

Table 4. Control results for thermal resistance of the metal outer body and the PVC plastic inner liner.

M	R material	k (W/m.k)	t,opt (mm)		Thermal Resistance (k/W)	
			Fridge	Freezer	Fridge	Freezer
1	PU Foam	0.0215	30	50	1.3953	2.3256
2	Fumed Silica VIP	0.0037	10	20	2.7027	5.4054
3	Glass Fiber VIP	0.0029	15	40	5.1724	13.7931
4	Alternate Core VIP	0.0076	15	40	1.9737	5.2632

Table 5. Conductive thermal resistance results for the fridge and freezer of each material using their optimal thicknesses.

M	R material	Total Thermal Resistance, Rtot=Ri+Rmaterial+Ri (k/W)		Rate of Heat Loss (W)		Price Estimation (RM/m^2)
		Fridge	Freezer	Fridge	Freezer	
1	PU Foam	1.3984	2.3287	14.3018	19.3244	5650.61
2	Fumed Silica VIP	2.7058	5.4085	7.3916	8.3203	14215.74
3	Glass Fiber VIP	5.1755	13.7962	3.8644	3.2618	10706.41
4	Alternate Core VIP	1.9768	5.2662	10.1176	8.5450	11896.01

Table 6. Rate of heat transfer results for each material through the fridge and freezer.

M	R material	k (W/m.k)	Thermal Resistance (k/W)
1	PU Foam	0.0215	0.1395
2	Fumed Silica VIP	0.0037	0.8108
3	Glass Fiber VIP	0.0029	1.0345
4	Alternate Core VIP	0.0076	0.3947

Table 7. Conductive thermal resistance results of each material at 3 mm of thickness.

M	R material	Thermal Resistance (k/W)	Total Thermal Resistance, Rtot=Ri+Rmaterial+Ri (k/W)	Rate of Heat Loss (W)	
				Fridge	Freezer
1	PU Foam	0.1395	0.1426	140.2408	315.5419
2	Fumed Silica VIP	0.8108	0.8139	24.5734	55.2902
3	Glass Fiber VIP	1.0345	1.0376	19.2760	43.3710
4	Alternate Core VIP	0.3947	0.3978	50.2748	113.1183

Table 8. Rate of heat transfer results for each material using constant thickness of 3 mm.

Contribution:

Name	Contribution
Muhammad Arslan Babur	Sample Data Research, Literature Review (Study of insulation materials and costs), Introduction, Conclusion. PPT Slides,
Ahmed Mohamedali Ahmed	Analysis of Heat Transfer (Sketching & Methodology). Sample Data research (Calculation), Literature Review, Calculation, Video participant
Mazen Omar Mohamed	Discussion(+ Sustainability), Sample Data research (Analysis in Discussion and Sustainability), Literature Review (Sustainability) Video Editing